GLACIERS

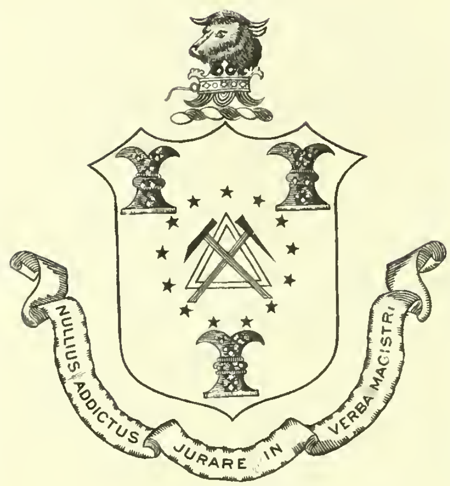
OF THE

CANADIAN ROCKIES AND SELKIRKS

BY

WILLIAM HITTELL SHERZER

FOR THE INCREASE AND DIFFVSION OF KNOWLEDGE AMONG MEN
PER ORBEM
SMITHSONIAN INSTITVTION WASHINGTON 1846



Ex Libris
Charles Willard Hayes

SMITHSONIAN CONTRIBUTIONS TO KNOWLEDGE

PART OF VOLUME XXXIV

GLACIERS OF THE CANADIAN ROCKIES AND SELKIRKS

(SMITHSONIAN EXPEDITION OF 1904)

BY

WILLIAM HITTELL SHERZER, Ph.D.

(No. 1692)

CITY OF WASHINGTON
PUBLISHED BY THE SMITHSONIAN INSTITUTION
1907

Commission to whom this Memoir has been referred :

THOMAS CHROWDER CHAMBERLIN
HARRY FIELDING REID
GEORGE PERKINS MERRILL

The Knickerbocker Press, New York

ADVERTISEMENT.

Doctor William H. Sherzer, Professor of Natural Science at Michigan State Normal College, has brought together in the present memoir the results of an expedition undertaken by the Smithsonian Institution among the glaciers of the Canadian Rockies and Selkirks in the year 1904. The general objects of the research were to render available a description of some of the most accessible glaciers upon the American continent, to investigate to what extent the known glacial features of other portions of the world are reproduced in these American representatives, and to ascertain what additional light a study of similar features here might shed upon glacier formation and upon some of the unsettled problems of Pleistocene geology.

A systematic survey was made of the Victoria and Wenkchemna glaciers in Alberta and of the Yoho, Asulkan, and Illecillewaet glaciers in British Columbia, located about two hundred miles north of the boundary of the United States. The largest of these is the Yoho Glacier, extending more than three miles below the névé field, and a mile in width for two-thirds of its length. Doctor Sherzer investigated various surface features of each of these glaciers, the nature and cause of ice flow, the temperature of the ice at various depths and its relation to air temperature, the amount of surface melting and the possible transference of material from the surface to the lower portion; their forward movement and the recession and advance of their extremities, and the general structure of glacial ice.

In summarizing the most important results Doctor Sherzer discusses the indicated physiographic changes in the region during the Mesozoic and Pleistocene periods; the question of precipitation of snow and rain, and the effect of climatic cycles on glacial movements, the structure of the ice as to stratification, shearing, blue bands, ice dykes, glacial granules, and the possible methods of their development. In discussing the theories of glacial motion the author expresses his conviction that the nature of the ice movement can be "satisfactorily explained only upon the theory that under certain circumstances and within certain limits ice is capable of behaving as a plastic body, that is, capable of yielding continuously to stress, without rupture," but "the plasticity of ice, a crystalline substance, must be thought of as essentially different from that manifested by such amorphous substances as wax or asphaltum."

Doctor Sherzer also discusses the cause of the richness and variety of coloring of glaciers and glacial lakes.

In accordance with the rule of the Institution this paper has been referred to a commission consisting of Professor T. C. Chamberlin, of the University of Chicago; Professor Harry F. Reid, of Johns Hopkins University, and Doctor George P. Merrill, of the United States National Museum, and upon their favorable recommendation is published in the series of "Smithsonian Contributions to Knowledge."

Richard Rathbun,
Acting Secretary.

Smithsonian Institution,
Washington, D. C., January, 1907.

PREFACE.

The five glaciers selected for investigation are located in Alberta and British Columbia, along the line of the Canadian Pacific Railway. They represent the great snow-ice masses which accumulate, season after season, upon the higher slopes and within the amphitheaters of the Selkirks and Canadian Rockies, the slow downward movements of which prevent indefinite accumulation and bring these great ice bodies to a level where complete melting may occur and the waters again be put into circulation. The observations here described were begun by the writer in the summer of 1902 and continued through the seasons of 1903, 1904, and 1905; the entire field season of 1904 being devoted to the surveys and more detailed studies.[1] Camps were established in the immediate vicinity of the glaciers selected and they were kept under almost continuous observation during the hours of daylight. Beginning with the nose of each glacier, surveys around either side to the névé field were made with plane-table, transit, or compass; the measurements being with a steel tape. It was found impracticable and unnecessary to traverse the névé areas and those portions mapped were drawn from field observations and original photographs together with maps and illustrations from the Canadian Topographic Survey, and other sources. The writer was ably assisted by Mr. DeForrest Ross and Mr. Frederick Larmour, to whom he desires to make grateful acknowledgment for intelligent and faithful service, rendered often under trying circumstances. During the latter part of the season of 1905 very efficient assistance was rendered by Messrs. E. W. Moseley and O. K. Todd.

Being the most accessible glaciers upon the American continent it was desired to render available as complete a description as time and facilities would permit and to ascertain to what extent the known glacial features of other portions of the world are reproduced in these American representatives. It was hoped that a study of the same features, produced under somewhat different conditions, might shed additional light upon their method of formation and upon some of the unsettled problems of Pleistocene geology. A disproportionate amount of time was devoted to the Victoria Glacier, at the head of the superbly beautiful Lake Louise Valley, since this glacier is geologically the most interesting and may well be taken as a type by students of glaciology. A delightful camp site lies under the lee of the outer massive block moraine and a still more picturesque one farther up, on a low shoulder of Mt. Whyte, over-

[1]A preliminary report upon the expedition appeared in May, 1905, in the "Smithsonian Miscellaneous Collections," vol. 47, Quarterly Issue, pp. 453 to 496.

looking the small lakelets. Students who may carry this report into the field generally desire an explanation which they can put to the test, upon the spot, and so an attempt has been made at interpretation of the various phenomena described. The value of such interpretation will be known only after others have passed judgment upon the same features and more extended observations are available.

Numerous forest fires in the season of 1904 prevented distant photography, on account of the smoke or haze, but through the courtesy of the Dominion Topographic Survey and of the Detroit Publishing Company we are permitted to reproduce some of their general views, obtained under favorable conditions. In addition to the views so used the writer is indebted to Captain Eduard Deville, Surveyor General of Dominion Lands, and his Chief Topographer, Arthur O. Wheeler, for a series of maps and photographs and much information concerning the regions under study. To the Director, R. F. Stupart, of the Canadian Meteorological Service, to the Assistant Director, B. C. Webber, and to Mr. N. B. Sanson, very grateful acknowledgment is made for meteorological data relating to British Columbia and Alberta and for the use of instruments kindly placed at the disposal of the expedition. Very sincere thanks are hereby tendered also to Prof. Joseph B. Davis, of the University of Michigan, and to Prof. Elmer A. Lyman, of the Michigan State Normal College, for the use of surveying instruments. The writer further desires to express his deep gratitude to the officials and employees of the Canadian Pacific Railway, who permitted the use of their Swiss guides for the necessary higher climbing and in many ways rendered very substantial assistance to the expedition. Finally to the packers and outfitters, Messrs. Robert W. Campbell and George W. Taylor, with their indispensable though often unwilling cayeuses, the writer desires to gratefully acknowledge the most generous and courteous treatment.

W. H. Sherzer.

The Michigan State Normal College,
Ypsilanti, Mich., December, 1906.

TABLE OF CONTENTS.

CHAPTER III.

Victoria Glacier (continued).

CHAPTER IV.

Wenkchemna Glacier.

CHAPTER V.

Yoho Glacier.

CHAPTER VI.

Illecillewaet Glacier.

CHAPTER VII.

Asulkan Glacier.

CHAPTER VIII.

Summary and Conclusions.

LIST OF ILLUSTRATIONS.

Mt. Lefroy. Mt. Victoria. Mt. Whyte.

Mount Victoria and Lake Louise, Alberta, Canadian Rockies. Reproduced by courtesy of Detroit Photographic Co.

GLACIERS OF THE CANADIAN ROCKIES AND SELKIRKS

(Report of the Smithsonian Expedition of 1904.)

By William Hittell Sherzer, Ph.D.

CHAPTER I.

INTRODUCTION.

1. Geographical Data.

a. Physiographic features.—The Canadian Pacific Railway crosses the Rockies and Selkirks between north latitude 51° and 51° 30′, working its way up the left bank of the Bow River and its small tributary Bath Creek, to the Kicking Horse Pass, attaining an altitude of 5,329 feet above sea-level. Upon the more abrupt western slope of the Rockies the road follows the left bank of the Kicking Horse River to its junction with the Columbia, crosses this great waterway of the mountains, and slowly ascends the eastern slope of the Selkirks along the left bank of the Beaver. The summit of the Selkirks, Rogers' Pass, is crossed at an elevation of 4,351 feet, whence there is rapid descent along the swift-flowing Illecillewaet to the Columbia again, which has encircled the system to the north, forming the "Big Bend." These transverse mountain valleys are lined with most majestic peaks, many of them rising a mile above the valley floor and furnishing some of the grandest of mountain scenery upon the American continent. The highest peak in the Rockies, seen from the railway, is Mt. Temple, with an elevation of 11,627 feet, and in the Selkirks, Mt. Sir Donald, 10,808 feet. Numerous peaks range from 10,000 to 11,000 feet and are believed to culminate to the northward in latitude 52° to 53°.

The Rockies and Selkirks, together with the Gold and Coast ranges to the west, make up the Great Cordillera in this part of Canada. North of the international boundary this great system is much narrower than in the United States,

having a total width of about four hundred miles, and the component ranges are straighter and more regular. The systems are progressively higher from the coast eastward, culminating in the Rockies proper, which stand as a lofty buttress along the western margin of the great central plains. Between the Coast and the Gold ranges there lies an interior plateau a hundred miles wide with an average elevation of about 3,500 feet above sea-level. The Gold, Selkirk, and Rocky systems are separated by the Columbia and the Columbia-Kootenay valleys, made by the action of water and ice along the strike of the geological formations, assisted probably by some dislocations of the strata.

The Rocky Mountains, or as formerly called, the Stony Mountains, consist of an imposing array of parallel ranges with a general trend in this region of north-northwest to south-southeast, separated by longitudinal valleys and attaining a total breadth of 40 to 50 miles. Compared with the systems to the west they are strikingly rugged in character and free from vegetation. Skirting the eastern border, and a part of them both geologically and structurally, are the "foot-hills," consisting of folded parallel ridges, reaching out 15 to 20 miles and merging into the "plains" at an elevation of about 3,300 feet.

b. Streams.—The main streams occupy the longitudinal valleys for a portion of their course, leaving the mountains by the transverse valleys, which extend into the foot-hills. According to Dawson the base-level of the streams upon leaving the mountains to the eastward is about 4,360 feet, while to the west it is about 2,450 feet above sea-level. Upon the eastern slope of the Great Continental Divide the waters are gathered into the Saskatchewan and reach the Atlantic Ocean by way of Hudson Bay; while those to the west drain into the Columbia River and work their way to the Pacific Ocean. As pointed out by Dawson, the actual water parting does not correspond entirely with the highest crest line of the mountains, but lies to the eastward, in which direction it seems to be moving. Between the international boundary of north latitude 49° and 52°, the Rocky Mountains are sharply separated from the Selkirks to the west by the Columbia-Kootenay Valley, which maintains a considerable breadth and a remarkably straight course through more than three degrees of latitude. This valley is filled with drift materials to a considerable depth and is undergoing but little erosion, the river simply cutting tortuous channels through the loose deposits. The eastern side of the valley is generally steep and escarpment-like, while the western is rounded and wooded. The Columbia starts within a mile and a half of its southward-flowing tributary, the Kootenay, and moves northwestward in a great sweep as though intent upon capturing the drainage of the region before starting for the sea. In this great fold it encloses and sharply limits the less rugged, but picturesque, Selkirk System, with its subdued outlines and forested slopes. Some of the eastern ranges are continuous and have the same general trend as those of the Rockies, but, in general, there is less regularity and continuity in the arrangement of crests and peaks, and they do not attain as great a height. The drainage is all into the Columbia River, and the streams are unable to develop any considerable

size. Being so largely glacier fed here, as well as in the Rockies, the streams maintain themselves during the summer months, but reach their highest stage in the late spring, or early summer, from the melting of the snows, when the Columbia may rise 30 to 40 feet above its usual level. The streams are generally turbid with glacial sediment that gives them a milky, or yellowish, appearance, changing to green and, upon the loss of the sediment, to a blue color wherever the water is of considerable depth. The lakes of the region owe their origin mainly to former glacial action, consisting either of rock-basins, or of depressions in the glacial or fluvio-glacial deposits. Certain ones have been dammed back by morainic material deposited either beneath or at the extremities of glaciers of greater extent than at present. Those lakes which receive glacial sediment, or which are shallow, have a greenish cast, while those free from sediment and of moderate to considerable depth are rich blue.

c. Glaciers selected for study.—The glaciers selected for study lie close to the main crests of the systems above described, between north latitude 51° and 52°, and west longitude 116° and 117° 30′, from 160 to 200 miles north of the international boundary between the United States and Canada. They are but a few of a series available for study, those being selected which are most easily reached by well established trails. They are at such low altitudes that one may comfortably ride almost to the nose of each and none require climbing except to reach the névé regions. The two most easterly of the glaciers here discussed, the Victoria and Wenkchemna, lie east of the Great Divide in Alberta, the other three are west in British Columbia.

2. Historical Data.

The establishment of the international boundary to the south, along the 49th parallel, and the opening of the railway in 1885 called for geographic, geologic, and topographic work which was started by the various Dominion departments concerned and is still in progress. Dr. George M. Dawson began his work in 1874 along the boundary and extended it northward to include the region pierced by the railway, where he was assisted by R. G. McConnell. Topographic work of a preliminary nature, along the line of the railway, was begun in 1886 by J. J. McArthur. Photographic methods were introduced into the survey in 1889 by Director Deville and the accompanying triangulation of the "railway belt" placed in charge of W. S. Drewry, D. L. S. The same year Mr. St. Cyr made a survey along the upper Columbia, between the Selkirks and Rockies, and in 1896 he and McArthur continued the work from Revelstoke down the Columbia and Arrow Lakes, with the view of connecting the surveys of the railway belt with those of the boundary commission.[1] Two topographic maps, upon a scale of two miles to the inch, were issued in 1902 by the Department of the Interior, under the direction of James White, geographer. These are the Banff and Lake Louise sheets and are issued by the department at

[1] The reports of the work of McArthur, Drewry, and St. Cyr will be found in the Annual Reports of the Canadian Dept. of the Interior for 1886, 1888 1889, 1890 1891, 1892, and 1893.

Ottawa. The topographic work of the mountains is now in the hands of Mr. Arthur O. Wheeler and there is being issued an enlarged map (scale 5,000 feet to an inch) of a section of the mountains lying between the railway and the Great Divide and extending from the Kicking Horse to the Vermilion Pass. This map includes completely the regions surrounding the Victoria, Horseshoe, and Wenkchemna glaciers, with corrected elevations, essentially the same territory covered by Wilcox's map, 1896, on the scale of an inch and a half to the mile. Based upon work done during the seasons of 1901 and 1902, there will be issued with vol. II of Wheeler's *Selkirk Range* an admirable piece of mountain mapping, extending from the Columbia to the Columbia, across the Selkirks along the line of the railway.

The opening of the railway and the wonderful attractions of the region brought in a body of non-professional explorers and mountaineers, among the first of whom was the Rev. W. S. Green, Carrigaline, Ireland. He spent the working season of 1888 in the Selkirks, using Glacier House as a base, and gathered material for an interesting volume, *Among the Selkirk Glaciers*, Macmillan & Co., 1890. The map accompanying the volume, originally published in the *Proceedings of the Royal Geographical Society*, vol. XI, 1889, was the first attempt at detailed mapping in the Selkirks. One year earlier than Green, in 1887, Messrs. George and William Vaux, Jr., of Philadelphia, visited Glacier House, secured a valuable collection of photographs and began a series of observations upon the glaciers to which frequent reference will be made in the later chapters of this report. During the closing decade of the last century, and the opening decade of the new, there has been much work done in the region of an exploratory and mountaineering character. There should be mentioned especially the names of Wilcox, Fay, Parker, Collie, Stutfield, Allen, Habel, Topham, Thompson, Huber, Sulzer, Noyes, and the English ladies Benham, Tuzo, and Berens. Besides three superbly illustrated and attractively written volumes by Wilcox, Wheeler, and, conjointly, by Stutfield and Collie,[1] there have been prepared a number of descriptive papers for the scientific societies and magazines. A bibliography of the region, full but not complete, will be found in *Appalachia*, vol. x, 1903, pp. 179 to 186. The Canadian artist, F. M. Bell-Smith, of Toronto, has spent many seasons in the mountains and, based upon the various maps, photographs, and original sketches, has prepared relief maps of the best known areas of the Rockies and Selkirks. Copies of these maps are placed in the hotels operated by the railroad.

It is not likely that these mountain valleys ever supported anything more than a scant Indian population, owing to the scarcity of fish, game, and available pasture. Providing food, en route, has always been a precarious matter for exploring parties. Aside from the marmot and rock-rabbit and an occasional porcupine, there is a strange and impressive feeling of desertion. The few

[1] *Camping in the Canadian Rockies*, Wilcox. G. P. Putnam's Sons, N. Y., 1896. *The Rockies of Canada*, Wilcox. Putnams, 1903. *Climbs and Explorations in the Canadian Rockies*, Stutfield and Collie. Longmans, Green & Co., N. Y., 1903. *The Selkirk Range*, Wheeler. Government Printing Bureau, Ottawa, 1905.

birds that one meets seem awed into silence by the grandeur of their surroundings. The mountain Crees had possession of the region at the coming of the white traders and trappers, but within rather recent time have been assimilated by the Stoneys, a tribe of Assiniboines, from the plains to the east.

3. Geological Data.

a. Stratigraphy. The first work of a geological nature in this region was by Dr. Hector in 1858 to 1860, as a member of the Palliser expedition, his observations being confined mainly to the Rockies and the region to the east. A geological map and numerous sections were prepared to accompany a paper presented to the Geological Society of London, in advance of the publication of the results of the expedition.[1] For detailed knowledge of the geology of the Rockies and Selkirks we are indebted mainly to Dr. George M. Dawson and his assistant R. G. McConnell, the former of whom began his work in 1874, as geologist of the boundary commission. The Bow River region was entered in 1881 and in the Annual Report of the Geological Survey for 1885 there was published a preliminary report upon the geology of the Rockies lying between the boundary and north latitude 51° 30′. The report was accompanied by a large scale geological map, which was followed the next year with a geological section by McConnell, approximately along the line of the 51st parallel of latitude. Work was extended westward into the Selkirks and, at the Washington meeting of the Geological Society of America, Dr. Dawson, in 1890, presented the results of his observations amongst these ranges.[2] The present Geological Survey, under the directorship of Robert Bell, is still at work upon the detailed study of portions of the region.

The Selkirks and Rockies consist of an enormous complex of sedimentary strata, 50,000 to 60,000 feet in thickness, underlain by crystalline rock. In age they range from the Archæan to the Laramie, at the close of which the final stages of upheaval were accomplished. The rock strata graduate in age from the west, eastward, and were folded and faulted by pressure from the west, by which they were forced against the resistant layers underlying the "great plains." The crystalline rocks of the series, of presumable Archæan age, consist of gray gneisses, passing into schists, and occur only along the western margin of the Selkirks, where they constitute the Shuswap series. No trace of them has yet been discovered in the Rockies. Overlying the series occurs the Nisconlith, with an estimated thickness of 15,000 feet, consisting of dark colored argillite-schists and phyllites, showing various stages of alteration from true argillites to micaceous schists. Interbedded layers of dark limestone and quartzite are seen in certain sections. Although the beds yielded no fossils they were referred to the Cambrian by Dawson, because of their relation to the

[1] "On the Geology of the Country between Lake Superior and the Pacific Ocean," James Hector, M.D., 1861, *Quart. Journal Geol. Society*, vol. XVII, pp. 388 to 445.

[2] "Note on the Geological Structure of the Selkirk Range," *Geol. Soc. of Amer.*, vol. 2, 1891, pp. 165 to 176. An extract from this paper is given in Wheeler's *Selkirk Range*, vol. 1, pp. 405 to 409.

crystallines and their supposed equivalency with strata of known Cambrian age in the Rockies to the eastward. The crest of the Selkirks, the region in which occur our snowfields and glaciers, consists of the folded Selkirk series, with an estimated thickness of 25,000 feet and believed to be of Cambro-Silurian age. The strata have been forced into a synclinal fold, which terminates to the eastward by a thrust fault, produced by the western half of a sharp anticline being thrust upward with reference to the eastern half. The rocks consist of gray schists and quartzites, passing into grits and conglomerates which weather to pale yellowish or brownish colors. The latter are often more or less schistose from pressure and other metamorphic agencies, silvery mica, or sericite, being developed. At times the strata are wrinkled and contorted.

Passing into the Rockies, to the eastward, we find them made up very largely of the representatives of the Nisconlith and Selkirk series just described, but known in the report of Dawson as the Bow River and Castle Mountain series. In the western part of the Rockies, adjacent to the Columbia, the upper and younger of the two is continued from the Selkirks, showing crumpling and folding, with metamorphism, but without faulting. The rocks are dipping eastward and have their "strike" parallel with the mountain ranges. Along the center of the range the folds are broad and sweeping, while eastward, for about 25 miles, there is a succession of thrust faults, running parallel with the ranges, the maximum vertical displacement being estimated at 15,000 feet. McConnell made out seven of these faults, giving rise to a series of massive mountain blocks resting in succession upon one another and forming escarpments to the east and relatively gentle slopes to the west. It was to this type of mountain that Leslie Stephen applied the suggestive term "writing-desk."

The ranges making up the central portion of the Rockies are of the Castle Mountain series (Selkirk series) and of Cambro-Silurian age. They are more regular and depart less from the horizontal than the strata to the east and west. Mt. Stephen, on the line of the railway, gives a 5,000-foot section of the series, one shaly band being remarkably rich in Cambrian trilobites. The total thickness of the series is estimated at 10,000 feet, as compared with 25,000 feet in the Selkirks, and consists of limestone and dolomite, with calcareous schists and shales. These rocks give the steep-sided, massive, block-like cliffs, typically shown in Castle Mountain, which has furnished the name for the series. These rocks extend lengthwise of the central ranges to the Yoho Glacier at the north and the Victoria and Wenkchemna glaciers to the south. At the base of Mt. Stephen. at the head of Lake Louise, and in the Bow River, there has been brought up from below by an anticlinal fold the "Bow River Group," or Nisconlith series of the Selkirks. This is of Cambrian age, estimated at 10,000 feet in thickness, and consists of quartzites and conglomerates. with dark gray, purplish, and greenish argillites.

b. Physiographic changes. When viewed from a high elevation the rough ridges and jagged peaks appear to blend, as far as the eye can reach, into a great plateau with a notably even sky-line (pl. II), giving the appearance of an

General view of Canadian Rockies from summit of Mt. Balfour (10,731 feet), looking west-northwest. Photographed, 1904, by Arthur O. Wheeler and reproduced through the courtesy of the Canadian Topographic Survey. Even character of sky-line signifies an uplifted and dissected peneplain.

uplifted peneplain, similar to that observed by Gilbert farther north in Alaska.[1] The upheaval of such a mass, by lateral pressure, would give rise to troughs and open gaping crevices parallel with the previously formed mountain folds and into these the drainage streams would, for the most part, be diverted. Deepened by stream action, widened by atmospheric agencies, and still further modified by Pleistocene glaciers, we have the longitudinal valleys of the Rockies and Selkirks. The transverse valleys, noted by Dawson as extending into the foot-hills and due to "causes not now apparent," probably mark the location of drainage streams developed while the peneplain was being formed and antedate the final upheaval of the region. That these valleys were occupied by extensive glaciers, presumably in Pleistocene time, is everywhere evidenced by the morainic accumulations, rounded rock contours, glaciated surfaces, extensive plucking, truncation of mountain spurs, amphitheaters, rock basins, and hanging valleys. The valleys generally were filled with ice to a depth of 2,500 to 4,000 feet during the maximum period of glaciation, the height, as pointed out by Wilcox, rarely falling below 7,000 feet above sea-level. Either because the mountains were so completely enveloped in ice and snow, or because of the nature of the final retreat, extensive terminal moraines were not formed in the main valleys. Ground-morainic deposits, however, hundreds of feet thick, occur in places favorable for their lodgment beneath the ice. Near Banff, in the Bow and Cascade valleys, Wilcox discovered evidence of two distinct till-sheets, the older highly charged with pebbles, with little clay, the younger consisting mainly of very hard clay.[2] In the extension of the Bow Valley to the eastward of the mountains, McConnell and Dawson found three separate till-sheets. The lowest and oldest of these appeared to have been entirely derived from the mountains and to pass eastward gradually into the "Saskatchewan gravels" of the plains. For this formation Dawson suggested the term "Albertan,"[3] which he regarded as of pre-Kansan Age.

The upper two boulder-clays contained rock fragments of both eastern and western origin, each variety preponderating in the direction of its origin, showing a commingling of the deposits of the Cordilleran and Hudson Bay ice sheets. The middle of the three till-sheets Dawson correlated with the Kansan and the upper with the Iowan (p. 509). In the light of our present knowledge the upper would be referred to the *Illinoian*, which succeeded the Kansan in the upper Mississippi Valley and was of much wider extent than the Iowan. The correlation of these sheets with those observed at Banff has not yet been made.

c. Lakes. In the very interesting paper above referred to, Wilcox recognizes four types of lakes in those portions of the Canadian Rockies which came under his observation:

First—Lakes lying in depressions of the valley drift, often in chains of

[1] *Harriman Alaska Expedition*, vol. III, Glaciers and Glaciation, Gilbert, p. 183.

[2] "A Certain Type of Lake Formation in the Canadian Rocky Mountains," *Jour. of Geol.*, vol. VII, 1899, p. 249.

[3] "Note on the Glacial Deposits of Southwestern Alberta," *Jour. of Geol.*, vol. III, 1895, p. 510. See also note on page 384, vol. III, *Geology*, by Chamberlin and Salisbury.

three, or four, and especially numerous near the summits of the mountain passes. These lakes show no regularity in form, or location, are usually shallow, and frequently have neither inlet nor outlet.

Second—Lakes dammed by terminal moraines. In the same class may be included those dammed by alluvial cones, or deltas formed in preëxisting lakes.

Third—Lakes lying in rock basins, excavated by former glacial action.

Fourth—A special type of lake, of which Lake Louise is an example, formed just within the mouth of a tributary valley. These lakes are leaf-shaped and from three to ten times longer than they are wide. They owe their existence to the presence of a ridge of ground-morainic material, thrown across the mouth of the tributary valley from the up-stream side and curving gently out into the trunk valley. These ridges have apparently been formed beneath the ice, when the valleys carried glaciers, by the joint action of the tributary and trunk glaciers. The lakes may be shallow and so filled with silt that they are reduced to swamps, or, where the ice was especially active, as in the case of Lake Louise, the depth may still be surprisingly great. As recognized by Wilcox, these lakes may present a combination of the rock-basin and morainic-dam types.

d. Alterations in drainage. In a region of the character above described, exposed for countless ages to the effects of weather, water, and ice, marked alterations in the drainage would be expected, such as reversals, stream capture, and the migration of divides. A study of the Columbia-Kootenay Valley has shown that the upper 200 miles of the Columbia flowed at one time to the south, instead of encircling the Selkirks to the north as at present. This must necessarily have been the case so long as that portion of the valley known as the "Big Bend" was in possession of the ice. The withdrawal of the glaciers into the tributary valleys would permit the present northward flow from the Columbia Lakes while the Kootenay, flowing in the opposite direction in the valley to the east, enters the main valley, approaches within one and one-half miles of the head-waters of the Columbia, but completely skirts the Selkirks to the south before joining it. Upon the opposite side of the Rockies attention has been called by Dawson, McConnell, and Ogilvie to changes in the Bow and its tributaries. The long, slender Lake Minnewanka Valley, near Banff, was evidently the course of a prepleistocene valley that was occupied and modified by an ice stream during the maximum period of glaciation of the region. Dawson considered this to mark the former course of the Bow, which was deflected to the southeastward, along the strike of the soft Cretaceous shales, when the lake valley was occupied by ice.[1] From barometric observations made by Dawson, his assistant McConnell noted that the Ghost River opposite the Devil's Gap, the mouth of the Lake Minnewanka Valley, is considerably higher than the valley floor and concluded that the Ghost River turned and entered the mountains through this valley, joining thus the Cascade and with it forming a tributary

[1] *Annual Report of Canadian Geological Survey for* 1885, "Preliminary Report on the Physical and Geological Features of that Portion of the Rocky Mountains between latitudes 49° and 51° 30'," 1886, p. 141B.

of the Bow.[1] The topographic map of the region, issued in 1902, shows that the river opposite the Gap is fully 100 feet higher than the level of Lake Minnewanka and about 400 feet higher than the present level of the Bow in the vicinity of Banff. According to this view of McConnell the ice-filled Minnewanka Valley compelled the Ghost River to find for itself a new course across the foot-hills to the eastward, which it deepened sufficiently, assisted probably by the ice, to prevent the return of the river into its former course upon the withdrawal of the glacier from the valley. In 1904 Dr. I. H. Ogilvie examined the region and reached the conclusion that the upper Bow and Minnewanka valleys were formerly continuous and that the Bow Valley below Banff was occupied by a stream which cut back into the soft shales until it tapped the upper Bow and effected its capture. She concluded[2] that this had been accomplished in prepleistocene time and that the Lake Minnewanka Valley was occupied by a glacier, fed by hanging glaciers, which moved westward, rather than to the east, deepening the western end of the valley and forming certain morainic deposits about the western end of the lake. The lake itself and its southwesterly drainage would then date from the withdrawal of the ice from the Cascade and Minnewanka valleys. Dr. Ogilvie holds that the drainage in the Lake Minnewanka Valley before the advent of the glaciers was eastward.

The bed of the Bow River at Banff is approximately 4,500 feet above tide, while that of the Ghost River, opposite the Devil's Gap, is not far from 4,900 feet. The present Bow, in the same distance as that from Banff to this portion of the Ghost River, drops 300 feet, so that the bed of the Bow at Banff is some 700 feet lower than it should be in order to have the upper Bow leave the mountains by the Devil's Gap and thence by the lower Ghost River. All will grant that this is too much cutting to expect of the Bow in postpleistocene time and that Dr. Dawson's theory of the diversion of the Bow by the Pleistocene glaciers is untenable. Noting that the Ghost River has also been deepening its bed, with a much steeper gradient and presumably for as long a time as the Bow, the above 700 feet must represent the *excess* of cutting by the upper Bow, when compared with the Ghost, since its capture by the lower Bow, upon Dr. Ogilvie's hypothesis. We have no knowledge of the depth of the drift deposits opposite the Devil's Gap, but there is no reason to think that they would be any deeper there than in the valley of the Bow. The explanation that lies nearest at hand is that of McConnell, *viz.*, that the Ghost River upon reaching the foot-hills made a sharp turn and reëntered the mountains by the Devil's Gap, but was diverted eastward when the Minnewanka Valley became ice-filled. According to this hypothesis the valley of the Ghost from the Gap down should show less maturity than that above the Gap, except so far as it may have been modified by ice action. During the period of maximum glaciation the ice movement in the Minnewanka Valley must have been eastward,

[1] *Annual Report of Canadian Geological Survey* for 1886. Report on the Geological Features of a Portion of the Rocky Mountains, 1887, R. G. McConnell, p. 9D.

[2] "Geological Notes on the Vicinity of Banff, Alberta," *Jour. of Geol.*, vol. XII, No. 5, 1904, pp. 408 to 414.

any tendency towards a westerly movement being checked by the ice in the Cascade and Bow valleys. The westerly movement noted by Dr. Ogilvie was simply a minor episode toward the close of the Pleistocene glaciation.

4. Climatic Data.

a. Geographic distribution of moisture. The climatic conditions of this section of country are peculiarly dependent upon the physiographic features above outlined, combined with its proximity to the Pacific. The centers of the areas of low pressure commonly move in from the ocean to the northward of the region, give rise to westerly winds which convey the warmth and moisture of the Pacific currents across British Columbia and Alberta. At Nanaimo, upon Vancouver Island, separated from the mainland by 30 miles of strait, the precipitation records available show a rain- and snowfall combined ot 41.36 inches, only 5 per cent. of which falls as snow. Opposite, upon the mainland, the total precipitation at Vancouver rises to 63.06 inches, with 4 per cent. falling as snow. This increase is due to the Coast Ranges, having here a northwest-southeast trend, which compel the westerly winds to ascend their westerly slopes, by which rise the air is cooled and its capacity for holding moisture thereby diminished. At Agassiz, in the lower Frazer Valley, the precipitation is but slightly less, although it is located some 70 miles from the Strait of Georgia, up the broad open valley, and about 50 feet above sea-level. Records are available here since 1890, with the exception of the years 1891 and 1899, and give for the 14-year series an average precipitation of 62.02 inches, 6 per cent. of which falls as snow. Over the broad interior plateau which lies between the Coast and Gold ranges, the temperature is colder and the precipitation relatively slight. At Kamloops, with an elevation of 1,160 feet and in latitude 50° 41′, the combined rain- and snowfall averages but 10.66 inches. Passing eastward the air currents impinge upon the westerly slopes of the Gold Range, are again compelled to ascend to still higher altitudes, with the attendant loss of moisture. In consequence, the station of Griffin Lake, located in this range at an elevation of 1,511 feet, and 90 miles east of Kamloops, receives an average precipitation of 34.37 inches, or over three times as much as the latter place. Crossing the Columbia a still higher barrier is encountered in the impressive Selkirk system of ranges, and a correspondingly increased amount of moisture extracted from the still laden air currents. The records in the Selkirks are unfortunately meager, but they indicate a precipitation almost as great as that of Vancouver and Agassiz, and considerably in excess of Nanaimo and Victoria out in the Pacific. The station of Glacier House is located just west of the main crest of the Selkirks, in latitude 51° 16′ and at an elevation above tide of 4,093 feet. The average total precipitation here is 56.68 inches, of which 77 per cent. falls as snow. If the entire amount were precipitated as snow, as is practically the case upon the peaks and elevated névé fields, this would represent an average fall of over 47 feet. This heavy snowfall in the Selkirks and Gold Range has

necessitated the erection of numerous snow-sheds over the tracks of the Canadian Pacific Railway, to guard against the frightful avalanches which come crashing down the mountain slopes.

Although Donald is located but a few miles east of Glacier House, it is upon the lee slope of the Selkirks and in the Columbia Valley some 1,500 feet lower. The precipitation here drops to 25.39 inches. The still higher Rockies immediately follow, but the Selkirks have proven greedy and there is relatively little left in the way of moisture. Full precipitation data in the region of the crest ranges of the system are wanting. The snowfall at Field, however, averages about 27 feet, at practically the same elevation as that of Glacier House. If we assume that the same ratio holds here, between snow and rain, as at the latter place the precipitation at Field, lying just west of the main crest, would be about 42 inches. Passing the continental crest the currents are drawn to lower levels, they become warmed by their descent, and their capacity for retaining moisture increases. At Banff the precipitation for the 13 complete years available averages 20.14 inches, of which 39 per cent. falls as snow. Beyond the foot-hills, at Calgary, the precipitation is reduced to 16.64 inches, of which 28 per cent. is snow. The following table furnishes a summary of the climatic data of special interest in connection with this report.

TABLE I.

Climatic Data, from Records of the Canadian Meteorological Service.

Stations, arranged from West to East.	Latitude N.	Lorgitude W.	Distance from coast, in miles.	Elevation above sea-level, in feet.	Mean annual temperature.	Highest temperature observed.	Lowest temperature observed.	Average annual precipitation.	Percentage of precipitation as snow.	Number of years in observations.	Remarks concerning location.
Nanaimo	49°10′	123°57′	−30	117	48.7°	90.3°	−3.9°	41.36	5	5	East side of Vancouver Island.
Vancouver	49°17′	123°5′	10	136	48.0°	89.0°	6.0°	63.06	4	4	West slope of Coast Ranges.
Agassiz	49°14′	121°31′	70	52	47.7°	103.0°	−13.0°	62.02	6	14	In open valley of Frazer River.
Kamloops	50°41′	120°20′	270	1160	47.1°	101.0°	−27.0°	10.66	24	10	Interior plateau.
Griffin Lake	50°58′	118°31′	400	1511	44.6°	110.0°	−23.0°	34.37	37	10	Gold Range.
Glacier House	51°16′	117°30′	460	4093	36.9°	89.0°	−21.0°	56.68	77	5	Selkirk System.
Donald	51°29′	117°11′	470	2580	37.4°	97.0°	−45.0°	25.39	51	10	Columbia Valley between Selkirks and Rockies.
Banff	51°10	115°35′	550	4542	35.3°	88.7°	−48.8°	20.14	39	13	East of Continental Divide about 15 miles.
Calgary	51°2′	114°2′	600	3389	37.2°	95.0°	−49.4°	16.64	28	19	Just beyond the foothills of the Rockies

Quite in contrast with the still higher mountains of this same system to the south in the United States, the following factors conspire to yield the necessary meteorological conditions for extensive perennial snowfields and glaciers;—

the narrowness of the system, its proximity to the Pacific, the higher latitude, the arrangement of the Cordilleran ranges with respect to height, and the position of the region with reference to the ordinary paths of the great cyclonic areas. If these areas of low pressure commonly crossed the continent so that the path of their centres lay well within the United States, the prevailing winds would be easterly over this region. Such winds would be colder in the winter and warmer in the summer than those which now prevail and capable of supplying relatively little precipitation. There can be but little doubt that any great shifting of the paths of the cyclonic areas, either to the north or the south, would lead to a great reduction in the size of the glaciers of this region, and perhaps to their complete extinction.

b. Chinook winds. One of the most interesting and important climatic factors of this section is connected with the prevailing westerly winds and the north to south trend of the main mountain ranges, giving rise to the so-called "Chinooks." These winds must have been long familiar to the aborigines and voyageurs, but were first noted by Mackenzie about the year 1790 in the region of the Athabasca and Saskatchewan rivers, bringing clear, mild weather in the winter and spring.[1] He ascribed their warmth, very naturally, to the nearness of the warm currents of the Pacific, their progress over the snowfields being assumed to be too rapid to permit of their being cooled. The same winds are known in Montana and still farther south in Colorado, where they are known as "zephyrs" and "snow eaters." They also occur in South America with the passage of westerly winds over the Andes, having been described by Bishop in the vicinity of San Juan, Argentine Republic, under the name "zonda."[2] Here they were supposed to derive their warmth from volcanic sources. The chief characteristics of these, and similar winds are their warmth and dryness and consequent accompaniment of bright sky. They are most conspicuous in the winter and spring, but occur also in the summer and fall. Standing upon the Victoria Glacier, in midsummer, opposite the nose of Mt. Lefroy, one frequently notes gusts of balmy air sweeping down from the elevated snowfields and puzzles over the source of the warmth. The following graphic description of these winds will serve to get before the reader their climatic importance.

"The extreme severity of the winters in certain parts of our northwestern states, among the Rocky Mountains and along their eastern base, is much tempered by the prevalence of a mild westerly wind, locally called the chinook. Its name is derived from that of the tribe of Chinook Indians, living near Puget's Sound. It is said first to have been applied by the early Hudson Bay trappers and voyageurs, who, meeting the wind while travelling towards the Pacific coast, and finding it particularly strong and warm as they approached the lands of this particular tribe, called it the chinook wind.

"It is described as a soft, balmy wind, varying in velocity from a gentle

[1] *Voyages on the River St. Lawrence and through the Continent of North America to the Frozen and Pacific Oceans in the Years* 1789 *and* 1793, London, 1801, p. 138.

[2] *A Thousand Mile Walk across South America.* Boston, 1869. N. H. Bishop.

breeze to a steady gale. Though its temperature rarely exceeds 50°F, yet coming as it does when one is accustomed to a low temperature, it seems warm by contrast with the preceding weather. The thermometer often rises from below the zero point to 40° or 45° in a few hours, and the maximum temperatures of the winter months in the Rocky Mountain region nearly always are coincident with the occurrence of a chinook.

"The sky is usually clear while the warm wind blows, though observers often note a few leaden-colored clouds of a kind seen only during the chinook. These clouds are described as pancake-shaped, with peculiarly smooth, rounded edges, and stand apparently motionless, high above the mountain ranges.

"The continuance of a chinook is as uncertain as its coming. It may last a few hours or for several days. With a change of wind the temperature falls rapidly, and winter weather once more sets in.

"The chinook wind possesses to a remarkable degree the power of melting snow, for it is not only warm, but appears to be dry. Although a foot or more of snow may lie on the ground at the beginning of a chinook, it disappears within a very few hours, often seeming rather to evaporate than to melt. For this reason the chinook is most welcome to the cattlemen on the plains of Montana and Wyoming. In fact, without it, stock-raising would be almost impossible, as the dried grasses of the plains, on which the cattle subsist, would otherwise be buried the greater part of the winter. To a few, however, this wind, instead of being hailed with delight as a break in the cold of the winter, is a source of much discomfort."[1]

The scientific explanation of this type of wind was first given, in part, by the American meteorologist Espy,[2] and later completed by Helmholz, Tyndall, and Hann. Simply stated and adapted to the region under discussion, this explanation may be of interest to many into whose hands this report may fall. The presence of an area of low barometric pressure to the north gives rise to a system of rotary air currents, moving counter-clockwise about the center and constituting a great "whirl." The interposition of mountain barriers, such as those already described, with a north to south trend, compels the winds, which are westerly in the southern portion of the cyclonic area, to mount these obstructions, from the crests and through the passes of which the air is again drawn to lower levels through the suction of the great rotating mass. As the air rises upon the windward slope of the mountain range, it experiences less pressure from the surrounding air, is permitted to expand, and is, in consequence, cooled at the rate of 1° F. for each 180 feet of ascent. This cooling reduces the ability of the air to hold moisture and when the dew-point is exceeded precipitation must result. These facts account for the relatively large precipitation upon the western slopes of the Coast, Gold, and Selkirk ranges. When vapor is condensed there is liberated the so-called latent heat, which disappeared when the water was originally evaporated. It so results that while the air is being cooled by its own expansion, the consequent condensation of its moisture is supplying it with heat, and the actual cooling experienced after condensation begins may be 1° for every 300 to 500 feet of ascent. The amount of heat thus supplied to the

[1] H. M. Ballou: "The Chinook Wind," *American Meteorological Journal*, IX, 1892–93, pp. 541–547.

[2] *Fourth Meteorological Report*, Washington, 1857, p. 147.

ascending currents will obviously depend upon the amount of moisture condensed and the rate at which this condensation takes place. The air will reach the mountain crest at a higher temperature than if no moisture had been condensed; it is capable of retaining more of its moisture in consequence, to be carried to the leeward of the mountain range. In being drawn down the leeward slope of the mountain barrier the air is compressed, as it descends, owing to the greater weight of superincumbent air, and is still further warmed at the rate of 1° F. for every 180 feet of descent. As it is warmed its capacity for holding moisture is thereby increased and it becomes, relatively, more and more dry, although it may actually possess considerable moisture. Such a warm, thirsty wind is our chinook.

The temperature of the air about the peaks and mountain passes differs less in the winter and spring from that of the valleys and lower plateaus, so that the chinook is a more conspicuous feature during these seasons. It is also during these seasons that the cyclonic disturbances are the most pronounced. In the summer and fall the temperature about the peaks and passes is generally sufficiently below that of the lower levels so that, although the heating effect, due to the condensation of vapor and the compression of the air in its descent, may be actually as great, it becomes much less perceptible. During the most favorable season for the chinooks we may, theoretically, account for a sudden rise in temperature of 20° to 25° F., but occasionally it is much greater than this, sometimes amounting to 50°. Mr. E. B. Garriott mentions a rise of 43° in 15 minutes occurring at Ft. Assiniboine, Montana, Jan. 19, 1892.[1] In order to account for such a phenomenon we must postulate a correspondingly high temperature about the crests of the mountains, brought about by excessive and rapid condensation upon the windward slope, or by some other agency. As is well known the temperature about the crests of mountains is often considerably higher than that in the adjoining valley, giving rise to what are known as "inversions of temperature." Since the establishment of the meteorological station upon Sulphur Mountain, October, 1903, with an elevation of 7,459 feet, there have been some 300 such inversions noted up to the close of June, 1906. The following list of some of the most pronounced cases, with dates, is taken from data kindly supplied by Mr. N. B. Sanson, of the Banff station. The upper station is 2,917 feet above the lower and $1\frac{3}{4}$ miles to the south-southwest. Of the 206 instances sent, 163, or 79 per cent. of them, were noted in the morning; 26, or 13 per cent., in the evening, and 17, or 8 per cent., at noon. Of this number 101, or 49 per cent., occurred during the winter months, giving the most pronounced cases of temperature inversion. The spring and fall were each represented by 27 cases, or 13 per cent., while the remaining 51, or 25 per cent., were noted during the summer months.

[1] *Monthly Weather Review*, 1892, p. 23.

TABLE II.

INVERSIONS OF TEMPERATURE, BETWEEN THE BANFF AND SULPHUR MOUNTAIN STATIONS.

Data supplied by the Canadian Meteorological Service.
(Elevation Banff Station, 4,542 feet; Sulphur Mt., 7,459 feet.)

Date.		Time.	Banff Station.	Sulphur Mt. Station.	Difference.
Nov.	17, 1903	6.00 A.M.	—22.6° F.	—14.0° F.	8.6°
Jan.	5, 1904	6.00 A.M.	— 7.4°	16.0°	23.4°
"	" "	6.00 P.M.	— 6.6°	4.0	10.6°
Jan.	17, "	6.00 P.M.	— 1.6°	20.0°	21.6°
Mch.	2, "	6.00 A.M.	—19.1°	4.0°	23.3°
Aug.	26, "	6.00 A.M.	38.5°	44.0°	5.5°
Sept.	2, "	6.00 A.M.	33.8°	40.0°	8.2°
Oct.	25, "	6.00 A.M.	26.6°	35.8°	9.2°
Nov.	24, "	6.00 A.M.	— 1.4°	6.8°	8.2°
Dec.	24, "	6.00 P.M.	— 5.6°	3.5°	9.1°
Jan.	29, 1905	6.00 A.M.	— 7.3°	43.0°	50.3°
Jan.	30, "	6.00 A.M.	—22.2°	1.8°	24.0°
Feb.	3, "	6.00 A.M.	— 9.7°	4.2°	13.7°
Feb.	5, "	6.00 A.M.	—10.2°	10.5°	20.7°
Feb.	11, "	6.00 A.M.	—14.0°	36.2°	50.2°
Aug.	23, "	6.00 A.M.	30.4°	36.0°	5.2°
Sept.	4, "	6.00 A.M.	33.8°	46.0°	12.2°
Nov.	10, "	6.00 A.M.	26.6°	32.2°	5.6°
Dec.	1, "	6.00 A.M.	— 9.5°	2.3°	11.8°
Dec.	31, "	6.00 A,M.	— 6.2°	4.0°	10.2°
Apr.	22, 1906	6.00 A.M.	24.2°	35.8°	11.6°
June	24, "	6.00 A.M.	35.2°	52.0°	16.8°

Geologically the chinooks must exert an influence, the accumulated effect of which may be considerable. They remove much snow from the eastern slopes of the mountains, which might otherwise be available for glacier formation, raising the lower limit of the snow-line and rendering it more irregular. That portion of the melted snow which is not evaporated will course down the mountain slopes as water, accomplishing a different work than if it had remained solid. The alternate periods of thawing and freezing during the winter and spring will accelerate the disintegration of rock upon the eastern slopes of the ranges. By this means glaciers lying to the east of the mountain crests will receive a heavier load of rock débris from neighboring cliffs, talus deposits will be larger than otherwise, and soil formation go on at a more rapid rate. At Innsbruck, in the Alps, where the foehn winds blow upon an average 42.6 days in the year, the mean annual temperature is raised 1.08° F., or the equivalent effect of one degree of latitude.

c. Oscillations in climate. The problem of precipitation has been discussed thus far with reference to its geographic distribution over the region, and although a full discussion cannot be here introduced, there still remains the question of its distribution in time. Here again our data are far too scant for satisfactory generalization, but, so far as the evidence goes, it is in harmony with the theory that precipitation occurs in cycles, there being a series of years in which the total

amount is in excess of the normal, although it may fall below for some particular year of the series. This damp phase of the cycle is followed by a series of years during which the total amount of precipitated moisture is less than the normal for this number of years, although it may be in excess for some particular year. Based upon the meteorological data from 321 stations distributed over Europe, Asia, Africa, Australia, North and South America, Brückner discovered the length of the cycle to be 35.5 years,[1] the dry phase averaging slightly longer than the damp one. At neighboring stations the cycles may partially overlap and, in the case of coast regions, the phases may be completely reversed, as recognized by Brückner. Coincident with the damp phase there is a general reduction in temperature, an increase in the level of lakes and rivers, a rise in the ground-water level, a halting or advance of the front of glaciers. The following table shows at a glance such data as are available along these lines, compiled from publications of Heim, Richter, Brückner, and Hess. The glacial data refer mainly to the Alpine region. Constructed for any particular region the figures would necessarily differ more or less from those given. So far as the United States is concerned the dry phase through which we have just passed appears to have closed and we are entering upon another series of damp years. In the Canadian region under study the damp phase seems to have started about three or four years earlier than in the Great Lake region and the preceding dry phase about as long before.

TABLE III.

PERIODIC OSCILLATIONS OF CLIMATE, WITH THEIR EFFECTS UPON LAKE LEVELS AND ALPINE GLACIERS.

Precipitation.		Temperature.		Lake Levels.		Glaciers.	
Damp.	Dry.	Cool.	Warm.	High.	Low.	Advancing.	Retreating.
1591–1600		1591–1600				1595–1610	
			1601–1610				
1611–1635		1611–1635				1630	
			1635–1645				
1646–1665		1645–1665				1677–1681	
			1665–1690				
1691–1715		1691–1705				1710–1716	
	1716–1735		1706–1735		1720		
1736–1755		1731–1745		1740		1735	
	1756–1770		1746–1755		1760		1750–1767
1771–1780		1756–1790		1777–1780		1760–1786	
	1781–1805		1791–1805		1798–1800		1800–1812
1806–1825		1806–1820		1820		1811–1822	
	1826–1840		1821–1835		1835		1822–1844
1841–1855		1836–1850		1850		1840–1855	
	1856–1870		1851–1870		1865		1855–1875
1871–1885		1871–1885		1880		1875–1893	
	1886–		1886–		1892		1894–

[1] *Klima-Schwankungen seit* 1700, Edward Brückner, Wien, 1890, pp. 133–193.

Numerous factors conspire to prevent the movements of glaciers from being exactly coincident with the corresponding climatic phases. For the Swiss glaciers Heim found that, ordinarily, an advance began from 3 to 6 years after the opening of a damp-cool phase and reached its maximum in 4 to 10 years, but in the case of the longest glaciers the maximum position might not be reached until the close of the cycle itself. These facts partially explain the anomalous behavior often noticed in neighboring glaciers. When the Illecillewaet Glacier was first visited by the Messrs. Vaux, in 1887, it was standing close up against a small moraine, which it had just formed, or more probably assisted in forming during this period of halt. Since 1887 this glacier has been in constant retreat at an average rate of 33.2 feet per annum. In 1905 the retreat was found to have been reduced to 2 feet and the inference is that the glacier is preparing to advance. So far as we may judge from a study of this one glacier, the best known of the series, a damp-cool phase of the precipitation cycle closed in the early 80's, and was followed by a dry-warm phase, which lasted for 16 to 18 years, ending somewhere near the close of the century. The following quotation from Dawson furnishes confirmatory evidence of the existence of the preceding wet phase of the cycle, which was itself preceded by a dry phase.[1]

"Evidence of a remarkable character has been found, which tends to show that a somewhat rapid increase in the total annual precipitation, has taken place during late years, and deserves to be recorded here. The evidence referred to is that afforded by the abnormal height of small lakes, without outlets, occurring in regions characterized by moraine hills. These serve as natural gauges, but instead of measuring the actual rainfall give a result, dependent on this and the counteracting effect of evaporation. The abnormal character of the rise of the water in these lakes is shown by the facts that it has killed a belt of trees, some of large size, and at least fifty years in age, along parts of the margins of some of these lakelets. Both the Douglas fir and the yellow pine—the latter, never naturally growing even in damp soil,—have been found in numbers thus killed. The condition of the trees shows that they have been killed within a few years, and their size indicates that the waters of the lakes in question have not been for any considerable time during a period of 50 years or more, at the present high level. These observations were made in both 1883 and 1884. The lakelets observed to be so affected were numerous and scattered over a belt of country along the western part of the range [Rockies] for a length of about 140 miles."

Looking to the records of the Canadian Meteorological Service for still further evidence of the periodicity of the climate of the region, we find that only three of the stations have records sufficiently continuous and reaching far enough back to be of help. These stations are Agassiz, Banff, and Calgary and their averages are more nearly the real, but still unknown, normal. Average annual temperatures and precipitation for the mountain stations, based upon observations made between 1880 and 1897, will certainly be found later to be too high for the temperature and too low for the precipitation, while those averages based upon observations taken since 1897 will prove to yield too high a precipitation and too low a temperature. In table IV we place side by side the

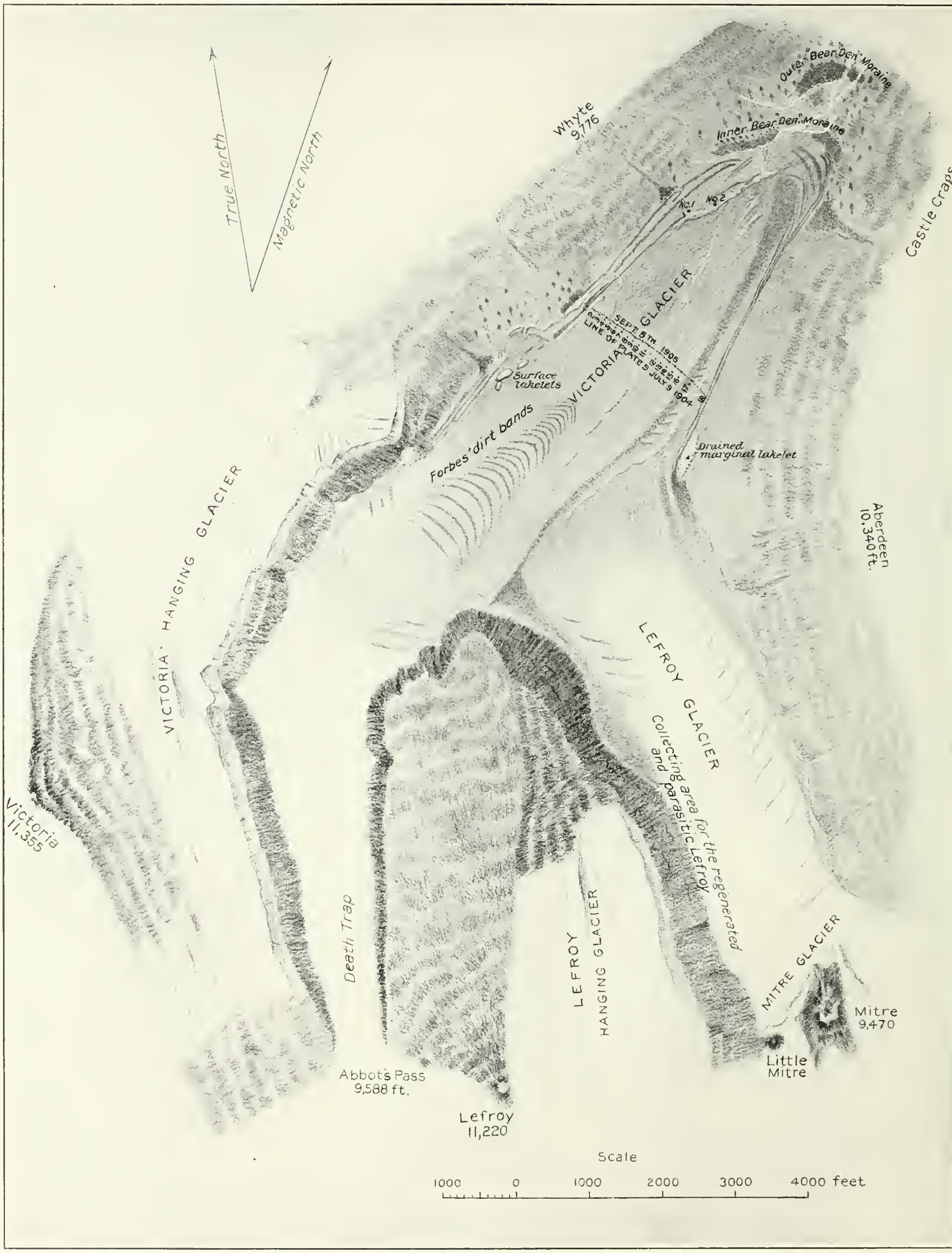
[1] *Geological Survey of Canada for* 1885, p. 32 B.

precipitation data for the above three stations, so far as such data are obtainable. In the first column for each station is given the total precipitation, in inches, the snowfall being reduced to rain upon the supposition that 10 inches of snow are equal to one of rain. In the second column is given, for each year, the actual deficiency, or excess, when the amount is compared with the *normal*, or average for the entire series of years. In the third column the actual precipitation appears as a *percentage* of the normal, while in the fourth there is given the *accumulated* excess, or deficiency, to or from the beginning of the year 1897. So far as we may be permitted to draw conclusions from all available data, the break between the damp and the dry phases of the precipitation cycle in this region occurred about 1897 in the Rockies and 1898 in the Selkirks and we may venture to predict that for another decade the precipitation will be in excess of the true normal for the various mountain stations. An examination of the Agassiz data, from the lower Frazer Valley, shows that while Banff and Calgary were deficient, this station was accumulating an excess and that since 1897 there has been a marked deficiency. The inference is that we have here an example of one of Brückner's exceptional coast regions, in which, although the precipitation is also in cycles, the crests of the great waves correspond with the troughs over the general surface of the earth. It is very unfortunate that the data from Vancouver, Nanaimo, and Victoria are not full enough to show whether or not they are included in this region.

TABLE IV.

PRECIPITATION DATA, BY YEARS, FOR CALGARY, BANFF, AND AGASSIZ.

Year.	CALGARY.				BANFF.				AGASSIZ.			
	Total precipitation.	Excess or deficiency.	Percentage of normal.	Accumulated excess or deficiency.	Total precipitation.	Excess or deficiency.	Percentage of normal.	Accumulated excess or deficiency.	Total precipitation.	Excess or deficiency.	Percentage of normal.	Accumulated excess or deficiency.
1885	12.91	−3.73	78	Accumulated deficiency 36.01 in.				Accumulated deficiency 17.80 in.				Accumulated excess 29.80 in.
1886	11.32	−5.32	68									
1887	15.69	−0.95	94									
1888	17.41	+0.77	105									
1889	11.59	−5.05	70									
1890	15.47	−1.17	93		19.54	−0.60	97		56.43	−5.59	91	
1891					16.48	−3.66	82					
1892	7.91	−8.73	47						67.78	+5.76	109	
1893	11.05	−5.59	66		10.88	−9.26	54		76.95	+14.93	124	
1894	11.63	−5.01	70						78.01	+15.99	126	
1895	16.00	−0.64	96						54.50	−7.52	88	
1896	16.05	−0.59	96		15.86	−4.28	79		68.25	+6.23	110	
1897	20.58	+3.94	124	Accumulated excess 35.97 in.	23.40	+3.26	116	Accumulated excess 17.83 in.	63.43	+1.41	102	Accumulated deficiency 29.76 in.
1898					20.58	+0.44	102		50.31	−11.71	81	
1899	26.15	+9.51	157		26.34	+6.20	131					
1900	17.57	+0.93	106		23.29	+3.15	116		72.00	+9.98	116	
1901	22.31	+5.67	134		19.27	−0.87	96		52.98	−9.04	85	
1902	34.57	+17.93	208		30.59	+10.45	152		54.68	−7.34	88	
1903	22.77	+6.13	137		24.82	+4.68	123		57.74	−4.28	93	
1904	10.82	−5.82	65		14.80	−5.34	73		54.67	−7.35	88	
1905	14.32	−2.32	86		16.00	−4.14	79		60.59	−1.43	98	
Normal	16.64				20.14				62.02			



Map of Victoria Glacier, Lake Louise Valley, Canadian Rockies. Surveyed and drawn by W. H. Sherzer, July, 1904. Field assistants De Forrest Ross and Frederick Larmour. Adjacent regions based upon maps of A. O. Wheeler and D. W. Wilcox.

CHAPTER II.

VICTORIA GLACIER.

1. General Characteristics.

The Victoria Glacier originates at Abbot's Pass, upon the crest of the Great Continental Divide which separates British Columbia from Alberta, flows due north for a mile between the precipitous walls of Mts. Victoria and Lefroy, makes an abrupt turn to the northeast and pursues a straight course for another two miles before wasting away in the Lake Louise Valley. The collecting area at the Pass is much restricted and narrows down to 600 to 700 feet, where the rocky cliffs upon either side begin to frown at each other from beneath the snow. These cliffs become higher and separate gradually, allowing the glacier to broaden to about one-third of a mile as it approaches the bend in its course. Rounding the nose of Mt. Lefroy the glacier receives its double tributary from the southeast, attains its greatest breadth of one-half mile, and for the last mile narrows regularly to its débris-covered nose. In this lower third of its length it lies between Mt. Aberdeen (elevation 10,340 feet) and Castle Crags upon the east and Mt. Whyte (9,776 feet) upon the west. A general view of the lower two-thirds of the glacier, with the tributary entire, is shown in plate IV, figure 1, while plate IV, figure 2, shows the upper portion and gives a lengthwise view of the tributary.

A Watkin mountain aneroid was carried to the crest of the Pass, July 22, 1904, and gave an elevation, when corrected, of 9,370 feet above sea-level. The more accurate methods of the Canadian Topographic Survey gave Wheeler 9,540 feet elevation for this same Pass, from which the descent through the so-called "Death-Trap" is rapid, requiring the cutting of steps in the snow when it is hard from freezing. Owing to the north-south direction of this part of the valley and the height of the bounding cliffs, the sun has little direct power and the glacier is permanently covered with snow which assumes a granular form, owing to the partial melting of the flakes, and constitutes the névé. This condition of the snow causes it to resemble granular tapioca and may be seen in the snows which, in more southern latitudes, linger until late in the spring. The névé-covered portion of the Victoria reaches an altitude of about 7,500 feet, or about 2,000 feet below the Pass, when, as the glacier turns to the northeast, the ice makes its appearance through the snow. The line of separation between ice and snow, as seen at the surface, is irregular and uneven, shifting with the season and from year to year. Winters of scanty snowfall, followed by bright warm summers, will send the névé line up the glacier; while winters of heavy snowfall and cool summers will cause this line to move toward the nose. Plate V, figure 2, shows the upper third of the glacier, leading to the Pass through the "trap," and the névé line in the foreground, as it appeared in July, 1904. Rounding Lefroy, the glacier descends rather abruptly some 400 to 500 feet, owing apparently to a sudden change in the inclination of its bed,

giving rise to a series of transverse crevasses. The lower one and one-half miles of the Victoria presents a remarkably even surface slope, suggestive of a correspondingly even bed, so that it may be ascended with entire safety by the most inexperienced. The nose reaches an altitude of about 6,000 feet, so that the average slope is at the rate of about 1,200 feet to the mile. For the lower half the surface slope is but 650 to 700 feet to the mile, or at the average rate of 7° to 8°.

In the névé region the surface of the glacier is concave, owing to the accumulation of snow along the base of the cliffs, this being permitted by the relatively small amount of heat radiation and reflection. For a short distance opposite Lefroy the cross sections of the ice stream have a horizontal surface line, while in the lower portion the surface is flatly convex, owing to the lateral melting caused by the rock walls and, to a greater or less extent, by the lateral drainage streams. (See the cross-section of the Victoria along the line of the steel plates; page 30.) It does not seem probable that the glacier attains any considerable thickness, the thickest portion, apparently, lying opposite the tributary where the ice may be 500 to 600 feet in depth. The nose is rounded, completely veneered by rock débris so as to conceal the ice, and perched up above the valley floor upon an old moraine which it has partially overridden, but has not had the strength to push aside (plate V, figure 1). The front here is steep, the angle being about 38°, and about 90 feet in height, with a series of gradually rising crests from the medial and right lateral moraines. Back from this nose some 2,000 feet, there is exposed a steep ice wall, 35° to 50°, which attains a height of 125 feet, and continues for about 800 feet. This now appears as the *side* of the glacier, but the position and form of the older moraines show that the front has been gradually swinging around into this oblique position, the cause of which is apparent from an inspection of the map. The eastern side of the glacier is much better protected by the right lateral moraine and by the much broader and closely placed medial. This portion of the front is thus prevented from melting, while the less well protected western half has been rapidly receding. Between this oblique ice wall and the real nose other smaller faces are developing and being enlarged with each season's melting.

2. Nourishment.

The main glacier is nourished in four ways, which may be separately recognized, as follows:

a. By the moisture directly precipitated into the valley between Mts. Victoria and Lefroy. The great bulk of this is in the form of snow, which probably amounts to about 25 feet per annum. The lesser amount in the form of hail, rain, dew, fog, and frost would also contribute to the substance of the glacier.

b. The funnel-like form of the valley, with its opening to the north, enables it to catch and retain large quantities of snow drifted southward by the north winds, as well as that which collects in the lee of Victoria when a west wind is

Mitre. Lefroy. Victoria.

FIG. 1.—General view of Victoria Glacier looking southward.

Mitre. Lefroy. Abbot's Pass. Victoria.

FIG. 2.—Lefroy Tributary. Victoria Glacier.

Aberdeen. Lefroy.

FIG. 1.—Débris-covered nose of the Victoria Glacier. July, 1904.

Lefroy. Abbot's Pass. Victoria.

FIG. 2.—Névé field of Victoria Glacier, looking southward through "death trap." July, 1904.

FIG. 1.—Path of an avalanche along Victoria névé. Photographed by De Forrest Ross, July, 1904. Note ice levees along the margin of the path.

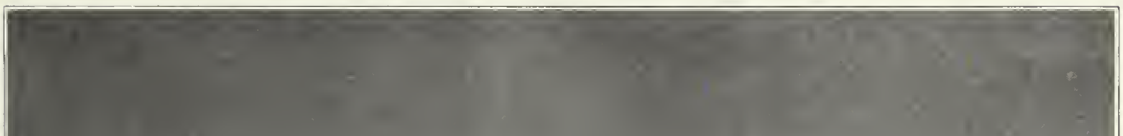


FIG. 2.—Hanging glacier upon Mt. Victoria as seen from summit of Mt. Aberdeen (elevation 10,340 feet). Photographed, 1903, by Arthur O. Wheeler.

blowing, or in the lee of Lefroy with an east wind. Thus because of its shape, position, and depth the upper valley is able to capture much more snow than it would ordinarily be entitled to.

c. Upon the opposing faces of Victoria (elevation 11,355 feet) and Lefroy (11,220 feet) large beds of snow accumulate during the fall, winter, and early spring. During the late spring and early summer much of this snow is precipitated into the valley as avalanches, with the roar of thunder and the blast of a tornado. It is the danger from this source that has suggested the name "Death-Trap," for the narrower portion of the valley, although no fatalities have yet occurred here. These avalanches may shoot directly across the valley, or they may turn and move along it lengthwise as shown in plate VI, figure 1. They must bring down numerous rock fragments, which are distributed completely across this portion of the glacier and incorporated into its névé.

d. A considerable portion of the snow which clings to the eastern shoulder of Mt. Victoria is compacted into stratified ice, and over an area of about one square mile there arises a true glacier perched up on the mountainside, with a slope that appears too steep to give it a foothold. Such a glacier is known as a "cliff glacier," or "hanging glacier" (plate VI, figure 2). It moves down the slope, probably with considerable velocity, and is avalanched into the valley upon the back of the Victoria Glacier, filling the air with ice dust. At the crest of the precipice the ice has an estimated thickness of 200 to 300 feet, from which great blocks, sometimes as large as a city square of buildings, are detached and fall vertically 1,200 to 1,500 feet. At certain places where the falls are more frequent there are built up débris cones of coarse granules upon the western margin of the glacier. This avalanched ice spreads over the glacier and is incorporated into its body along with more or less ground-morainic material which has been manufactured between the hanging glacier and its bed. When the weather is cool and cloudy these ice avalanches are infrequent, but upon a warm bright day, with much melting and more rapid forward movement of the ice, they occur every few minutes from some portion of the long front. On August 25, 1903, during the mid-portion of the day avalanches were noted as follows:

10:39 A.M.	moderate.	12:29 P.M.	moderate.
10:43	slight.	12:49	moderate.
11:05	slight.	12:52	slight.
11:27	slight.	1:11	moderate.
11:28	heavy.	1:18	moderate to heavy.
11:40	slight.	1:35	moderate.
12:20 P.M.	slight.		
12:27	moderate.	1:52	moderate.
		2:10	moderate.

Owing to its western and southern exposure the opposite face of Lefroy does not support a hanging glacier, although there is a suitable collecting area

for the snow. That which is not precipitated into the valley as avalanches melts away in the course of the summer and this water, along with that from Mt. Victoria, forms slender cascades, which are partially absorbed by the névé and, in part, work their way to the bed of the valley and are incorporated into the subglacial drainage. In these various ways the upper Victoria receives the precipitation from about two square miles of collecting area. Through pressure, rain, and surface melting, due to the intense solar action, as well as the chinook winds, this mass of granular snow is compacted into a very fine granular ice. Powerful winds sweep over the bare peaks and ridges and spread over the névé more or less fine matter, organic as well as inorganic. This material is concentrated at the surface, when sufficient melting has taken place, and gives a rather sharp line of demarcation between the older snow and that which falls freshly upon it. In consequence of the melting and the presence of the foreign matter, the névé acquires a characteristic stratification, which in the case of the Victoria persists to its nose. Owing to the avalanches of snow and ice from Mts. Victoria and Lefroy these strata are rendered more or less irregular. The great weight of this snow and underlying ice forces the entire mass valleyward and thus prevents indefinite accumulation.

3. Double Tributary.

a. Mitre Glacier; the host. Upon either side of the small peak known as the Mitre (elevation 9,470 feet), there descend two steep snow slopes, which give rise to two névé-covered streams of ice (see plate VII, figure 2). That to the right is intersected by a great crevasse, caused by the glacier drawing away from the snow and ice which adhere to the rocky slope, and forming what is known as the "bergschrund." This schrund renders this stream impracticable, but the other may be safely ascended with a guide, to the Mitre Pass leading over into Paradise Valley. Here from an elevation of 8,480 feet the descent is very rapid for about 1,200 feet, when the two streams unite into a single glacier, for which the name Mitre, first proposed by Allen for the entire tributary, may best be retained. For a very short distance the glacier is permanently covered with névé, but in midsummer this soon disappears and discloses a very weak and poorly defined medial moraine (plate VII, figure 2). It flows lazily down the straight valley, one and one-third miles, between Mts. Lefroy and Aberdeen, attains an average width of one-third to one-half a mile, and joins the Victoria with a breadth of 3,200 feet.

b. Lefroy Glacier; the parasite. Upon the eastern and northern slope of Mt. Lefroy, because of its exposure and other favorable conditions, there has arisen another hanging glacier similar to although smaller than that just described upon Mt. Victoria. Plate IV and plate VII, figure 1, give views of this elevated glacier, clinging to the steep mountain slope, the latter view being taken from the summit of Mt. Aberdeen, looking westward and from an elevation of 10,340 feet. From the steep, vertical ice face great blocks are avalanched 2,000 feet into the valley, much of the ice being ground into dust and shot

FIG. 1.—Hanging glacier upon Mt. Lefroy as seen from summit of Mt. Aberdeen (elevation 10,340 feet). Photographed, 1903, by Arthur O. Wheeler.

Aberdeen. Mitre Pass. Mitre. Little Mitre. Lefroy.

FIG. 2.—Double névé field of Mitre Glacier, July, 1904. Faulted névé strata are seen in left tributary and a bergschrund in the right. In foreground a snow-filled crevasse; beyond which lies the névé line.

out beyond the base of the cliff. Upon the western or Lefroy side of the upper half of the Mitre Glacier, there is thus heaped up a mass of pulverized ice, which is compacted by freezing into strata. This mass constitutes a new glacier, since the structure of the original one must have been destroyed by the plunge, with the exception of the granules and their fragments. Such a glacier is said to be "reconstructed," or "regenerated." Furthermore, this new glacier rests upon the back of the Mitre; is nourished differently; is of a different form; has its own distinct set of strata, unconformable with those of the Mitre; moves across the valley instead of lengthwise of it, and is accomplishing a totally different geological work. This glacier, for which the term Lefroy is appropriate, is one of the best known examples of what Forbes termed a "parasitic glacier,"[1] far better, indeed, than the type itself. It is parasitic in the sense that it is carried by its host, the Mitre, and in that it is nourished entirely by snow and ice which would be otherwise available for the host.

Just what is the structural relation of the Lefroy to the Mitre, the parasite to its host, can only be conjectured, since the contact was not observed and the plane of separation may not be at all distinct. There is, however, a very evident, deep-seated motion down the valley and an equally evident superficial motion across from the base of Lefroy to the foot of Aberdeen. The result of the latter motion is to carry most of the ground-morainic material, such as clay, sand, bruised and scratched pebbles and boulders, which has been manufactured beneath the hanging glacier of Lefroy, entirely across the valley and dump it in a great heap upon the eastern or Aberdeen side of the Mitre (plate VIII, figure 1, and plate XV, figure 1). The *front* of the parasitic Lefroy being parallel with the *side* of the Mitre, some of the ground-morainic deposit is arranged in ridges parallel with the side of the latter, in which form it is being dealt out to the Victoria. Until the above stated relations were discovered it was a serious puzzle to ascertain how a glacier could get its ground moraine upon its own back and arrange it in ridges parallel with its side (see plate XV, figure 1). That the material could not have come from Mt. Aberdeen was evident from the fact that it does not support a hanging glacier upon its western face, as shown in plate VIII, figure 2, although there is a buried mass of stagnant ice upon the northern shoulder. Avalanches of snow and the ordinary processes of weathering have brought down considerable angular material from Aberdeen which covers most of the ground-morainic deposit from the opposite side of the valley. While this ground-morainic material is being moved east-northeast by the Lefroy for a distance of 1,800 to 1,900 feet, it is also being carried north-northwest for a distance of about 3,800 feet by the underlying Mitre and the resultant motion is somewhat east of north. This will be made clear from an inspection of the map, plate III.

Opposite the large débris cone seen in plate IV, figure 2, upon the western side of the Lefroy Glacier, there is a marked depression in the surface of the ice and also across the entire tributary where it joins the Victoria, giving good

[1] *Travels through the Alps of Savoy*, James D. Forbes, Edinburgh, 1845, p. 201.

exposures of the outcropping edges of the strata, to be noted later. These depressions furnish confirmatory evidence that the general movement of the superficial layers is *across* and not parallel with the valley. The position of the left lateral moraine from the débris cone, above noted, to the Victoria, shows, however, that along the base of the Lefroy cliff the movement is normal and due to the Mitre, although the strata belong to the Lefroy. In consequence of this a relatively small amount of morainic material is captured from the Lefroy and delivered to the medial moraine of the Victoria at the nose of Mt. Lefroy. This double tributary joins the Victoria at an elevation of about 6,670 feet, having an average surface slope of 1,360 feet to the mile, and is at once compressed to about 600 feet, as compared with 3,200, or as $5\frac{1}{3}$ is to 1. There being no corresponding increase in the height of the ice, the inference is that the tributary delivers relatively little ice to the Victoria and that its movement is correspondingly slow.

4. Drainage.

a. Surface ablation. The drainage supply of the glacier originates from the rainfall over the glacier and adjacent mountain slopes, from the melting of the snow and ice in the region of the hanging glaciers, and from the general melting of the glacier itself and its tributaries. No definite data are available concerning the rainfall over the glacier and adjacent slopes. Owing to its greater altitude it would be much less than at Field and Banff and would practically all fall during June, July, August, and September. After heavy showers the streams from the mountain slopes are in many cases highly charged with sediment, those originating from the melting of snow being generally clear.

The temperature of the ice during the summer was found to be either just at the freezing point, or so near it that any addition of heat was sufficient to start the process of melting. In the abandoned drainage tunnel, to which reference will be made later, holes were bored into the ice wall, 140 feet back from the entrance, and a standard minimum thermometer inserted its full length. Owing to the course of the tunnel the point of observation was estimated to be 70 feet from the foot of the oblique ice wall and about 17 feet from the actual ice face (plate VIII, figure 4). During the week from July 31 to August 7, 1904, the readings were 31.8° F., 31.6°, 31.8°, 31.9°, 31.7°, and 32°. The maximum temperature of the air in the tunnel during the week ranged from 31.4° to 33.0° F. Owing to the warmth of the body and that of the candle used, it was found impracticable to get the temperature of the air at the same time that the temperature of the ice was taken.

In the rarified atmosphere at these high altitudes the midsummer sun strikes with surprising force and the surface ice, so near its melting point, is at once converted into water without changing its temperature. In the case of scores of observations made upon the surface streams of the series of glaciers the temperature was almost uniformly 32° F. In rare cases it was found to be a small fraction of a degree above. In order to secure some data for an estimate

Aberdeen. Mitre. Lefroy

FIG. 1.—Parasitic Lefroy Glacier being carried by Mitre Glacier. Morainic accumulation at base of Mt. Aberdeen consists mainly of *ground* moraine, manufactured beneath the hanging glacier on Mt. Lefroy and carried across the Mitre by the Lefroy.

FIG. 2.—Western face of Mt. Aberdeen, looking across Lefroy Glacier from surface of the Victoria.

FIG. 3.—Surface drainage stream upon Victoria Glacier.

FIG. 4.—Oblique front of Victoria Glacier, showing abandoned drainage tunnel. July, 1904.

of the rate at which surface ablation was taking place over the lower portion of the Victoria, accurate elevations were taken upon the series of steel plates used in determining the forward movement. The results are shown in table V, page 31, giving the total melting from July 13 to August 4, 1904, for a period of 22 days of midsummer. The maximum lowering of the ice surface occurred at plate No. 13, nearly two-thirds of the way across when measured from the west side, and amounted to 3.8 feet, or a daily average of 2.076 inches. This plate was located on a portion of the glacier least protected by rock débris. Although this lowering of the surface is due, in the main, to the sun's action and general effect of the atmosphere, usually above the freezing point in summer, there are other minor agencies which would tend to give the same result. One of these is the rain, 1.506 inches of which fell during the period of the observations. Other agencies are subglacial melting and subglacial erosion, longitudinal stretching, or a lateral spreading of the ice, all of which would tend to lower the upper surface. It should be noted, further, that in the 22 days this plate moved forward 60 inches and with the average surface slope of 7° to 8°, the plate would be lowered by this agency alone about one-third of an inch daily. Making this correction the actual ablation, from sun, atmosphere, and rain, would amount to about 1.74 inches daily and for the two main months of July and August would give a total of about 9 feet. Observations upon the lower Lefroy showed that the ice surrounding certain morainic heaps had been lowered during the season by about this amount. No glacial tables of this height can be found, however, because of the undercutting effect of the sun's rays and the consequent destruction of their pedestals. The broad medial depression lying just west of the medial moraine (see plate IV, figure 2, and cross section page 30) has been produced by the greater surface melting and this has been permitted by the thinner covering of rock débris, the ice of this portion of the glacier coming from the Lefroy side of the upper Victoria. This depression continues down the glacier for 2,200 feet, where it thins out, apparently from surface melting. With a forward motion here of about 64.5 feet annually, it would require 34 years for the ice to move from the line of plates to the oblique ice face, during which time some 306 feet of ice might be melted away. If the rate of melting and rate of forward movement remained constant, this number would represent the approximate thickness of the ice beneath plate 13. It is very probable that the rate of melting becomes less, owing to the concentration of rock débris at the surface, but it is also very probable that the rate of forward movement becomes also less as the ice diminishes in thickness. The work with the spirit level indicated that this plate was originally 393 feet above the lower margin of the ice in this depression, the difference of 87 feet representing the rise of the valley floor in this distance. If this latter figure is approximately correct the inclination of the bed is much less than that of the surface of the ice itself

b. Surface drainage. Over the entire névé area the water from the melting snow, as well as that from the rainfall, is absorbed into the body of the glacier

and refrozen, binding the granules together into an ice conglomerate. Where the ice itself is exposed and crevasses absent, the melted ice and rainfall are concentrated into more or less well defined channels, which persist from season to season. In the early morning the glacier is impressively quiet, the ice is dry, and many of the small pools are frozen over with a thin layer of ice. When the summer sun enters the valley the exposed ice becomes moist, small trickles of water unite into rills, that grow larger and larger from the union of innumerable others, and these form still larger brooks which empty their clear, ice-cold waters into the main drainage channels and, after a day of rapid melting, we have here roaring torrents. These streams slowly cut their way into the solid ice by mechanical erosion, assisted by the rock fragments which the water is able to move along, and by melting. The water being apparently at the melting point of the ice, 32° F., it is incapable of imparting heat to that over which it flows and the melting must arise from the conversion of its kinetic energy into heat. Such heat would be imparted to the ice, rendered latent in the process of liquefaction and the temperature of the water would not be sensibly raised. The question arose in the mind of the writer while studying these ice streams whether water at 32° is capable of *dissolving* ice at the same temperature, as it might dissolve rock salt over which it was flowing. So far as he has been able to learn the question has not been investigated, but if water does have any such effect upon ice under these conditions, it would help to explain the formation of these ice channels.

In the upper part of their courses these stream beds are generally free from débris and quite straight, but as the bed is broadened, boulders, too large for the stream to handle, slide in from the surface and the stream is compelled to go around. In this way a system of meanders is formed, as shown in plate VIII, figure 3, and the ice banks are rendered steep and, here and there, undercut by the rushing water. In the lower portions of the course the bed may contain considerable rock débris, but this has simply slid down from the surface and nowhere suggests an aggrading action of the stream. When the stream channel is contracted for any reason, the level of the water is raised, its velocity increased in consequence, and an ice basin cut out upon the down-stream side, filled with more quiet water. This is suggestive of the manner in which the Lake Louise rock basin, to be later described, may have originated when the entire valley was ice-filled.

In portions of the glacier intersected by crevasses it is obvious that surface streams, of any considerable size, cannot develop. The water escapes by an englacial or subglacial tunnel, to reappear at or near the nose. When a stream encounters such a crevasse, from which there is drainage beneath, it forms a small cascade and begins to cut a channel in the vertical face of the crevasse wall. If the velocity and volume of the water are sufficient, a corresponding channel may be produced in the opposite wall. As the lips of the crevasse are subsequently brought together by movements of the ice body, and the crevasse is healed, this small vertical channel persists and still furnishes an

FIG. 1.—First stage in formation of a moulin, Lefroy Glacier.

FIG. 2.—Marginal lakelet west side Victoria Glacier.

FIG. 3.—Inner end abandoned drainage tunnel, Victoria Glacier, July, 1904.

FIG. 4.—Mouth abandoned drainage tunnel, Victoria Glacier, looking outward. July, 1904.

escape for the surface stream. This is well shown in plate IX, figure 1, the small stream entering the nearly healed crevasse from the right. As the ice moves valleyward the drainage area of the stream may be enlarged, the amount of water correspondingly increased, and our glacial well, or "moulin," may be indefinitely enlarged both in diameter and depth. Since the water is introduced from above and escapes below, they are more like *wells*, turned wrong-side up. They may be found in various stages of development, the younger in the region of the open crevasses, the mature examples in the lower course of the glacier, where they have been carried by the general forward movement of the ice, and into which the surface torrent plunges with a sullen roar to unseen depths.

The main drainage stream of the Victoria Glacier starts near the nose of Mt. Lefroy, to the west of the medial moraine, and passes somewhat obliquely downward to a moulin, opposite the oblique ice face (plate IV, figure 1, and plate III). This stream drains that portion of the glacier over which the surface melting is the greatest. A second drainage stream originates near the above, but in the depression between the medial moraine and the Lefroy tributary. This stream collects the surface waters from the tributary and extends for one-quarter mile down the deep depression between the medial and right lateral moraines and disappears in a system of crevasses that cut this portion of the glacier.

Two short, but rather deep, drainage channels occur upon the western side of the glacier, lying upon the inner side of the left lateral moraine. One of these has incised the ice to a depth of 18 to 20 feet. Since these streams have probably occupied their present sites for many years it is rather remarkable that they have not completely cut through the ice to the rocky bed beneath. From the fact that they have not done so we are forced to conclude, either that the rate of cutting is surprisingly slow, or else that the glacier thickens in such a way that the bottoms of the streams are elevated with reference to the base of the glacier. It is possible that the longitudinal compression to which the glacier is subjected in its lower half may be sufficient to secure this result.

c. Marginal drainage. Upon the eastern side of the lower Victoria, along the base of Mt. Aberdeen and Castle Crags, there is no visible marginal drainage at present, but water may be heard trickling amongst the rocky débris. Just at the head of this depression, however, where the tributary joins the main Victoria, there is evidence of earlier drainage here, in the form of an abandoned lake bed, with a length of 500 to 600 feet. A small gravel delta was formed at the head, while the rest of the bed is filled with silt. A still smaller lakelet existed for a short time at the nose of Mt. Lefroy, in the depression between this side of the tributary and the Victoria. Upon the western side of the glacier there occurs a similar marginal lakelet, between the glacier and Mt. Whyte, fed by a mountain stream and a discharge stream from the glacier itself (plate IX, figure 2), which cascades over the lateral moraine from a dozen different places. The lakelet has an elevation of 6,554 feet, is largely filled with fine silt, and

contains a number of low islands, supporting some vegetation. The outlet stream is marginal for about 500 feet and then enters the side of the glacier.

d. General drainage brook. The subglacial and englacial streams are all united into a single stream which emerges from the base of the ice at an elevation of 6,127 feet and back about 1,000 feet from the real nose, upon the west side. This stream cascades over the coarse blocks of the terminal moraine, receives a small tributary from Mt. Whyte, and rushes headlong to the lake, one mile distant, dropping some 450 feet. In comparatively recent time the discharge was through a tunnel which is being rapidly destroyed by melting. plate VIII, figure 4, shows the entrance to this tunnel as it appeared in 1904 and plate IX, figure 4, furnishes an interior view looking out and down the valley. At this time the opening was 12 feet high by 7 feet broad and the tunnel could be entered for a distance of 160 feet, when it appeared to have been clogged by ground-morainic material. The opening narrowed rapidly toward the inner end (plate IX, figure 3) and the severe melting of 1905 showed that it connected with an englacial passage leading towards the main moulin. This difference in the size indicates that when the ceiling of the portion of the tunnel shown in plate IX, figure 4, was being fluted by torrential waters, the bed of the stream was at a considerably higher level than that there shown and that the stream worked its way down from an englacial to a subglacial position. The amount of water discharged through this tunnel was probably no greater than that at the present time through the present exit. The floor of the tunnel, at its entrance in 1904, had an elevation of 6,192 feet, or 65 feet above the present place of discharge.

During periods of minimum melting, and always in the early morning, the amount of water discharged from the glacier is relatively small. Late in the afternoon and evening of a day of rapid melting it gushes forth with great power and volume (plate X, figure 1). It was impracticable to measure the amount of discharge at this exit, but measurements were made at the delta where the stream enters the lake. So little additional water was being received at the time from the adjacent mountain slopes that the results secured represented approximately the flow from the glacier itself. An accurate cross-section of the stream was secured by taking the level of the bed for each foot, establishing a gauge, and determining the velocity from surface floats. A calculation of the flow was made, after a week of minimum melting, by averaging the flow at 9:00 A.M. and at 6:00 P.M. During this period there were 0.671 inch of rainfall near the nose of the glacier. A similar determination was made after a week of maximum melting, with 0.030 inch of rainfall. These results gave 73 and 93 cubic feet per second for the average flow. At the time of the minimum flow the water at the exit from the glacier was found to possess 0.230 oz. of sediment to the cubic foot and 0.506 oz. during the time of maximum discharge. This is enough to make the water decidedly turbid. The total amount of sediment carried out daily during the maximum discharge period was estimated to be about six tons, and one-third this amount for the

FIG. 1.—Drainage from Victoria Glacier after a day of much melting.

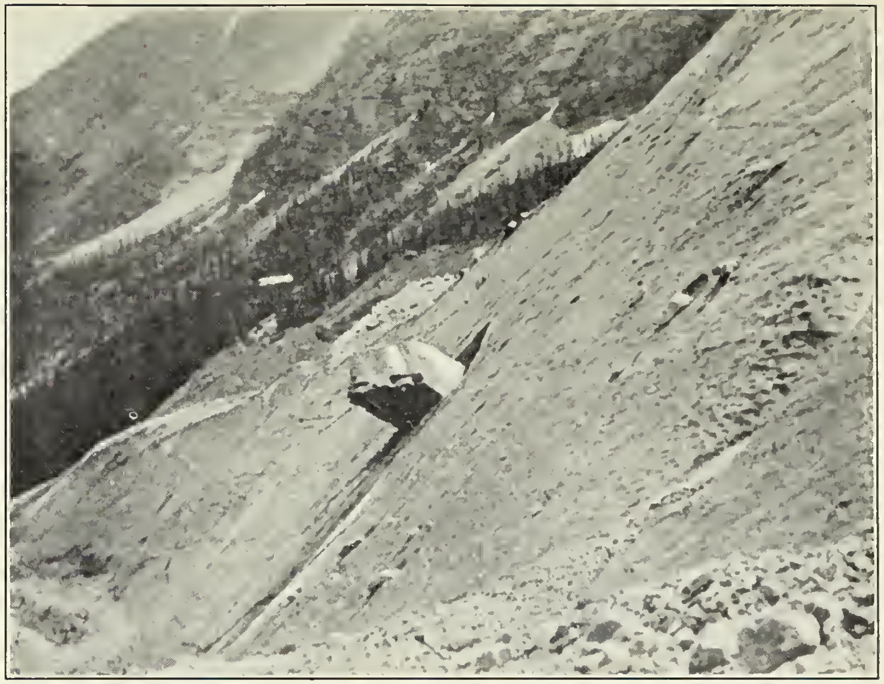


FIG. 2.—Reference boulder A, Victoria Glacier, still embedded in the ice. Photographed July 30, 1898, by Prof. Charles E. Fay.

FIG. 3.—Stratified ice front, Victoria Glacier. Reference boulder A in the middle foreground, August 23, 1903; seventy-six feet from ice margin.

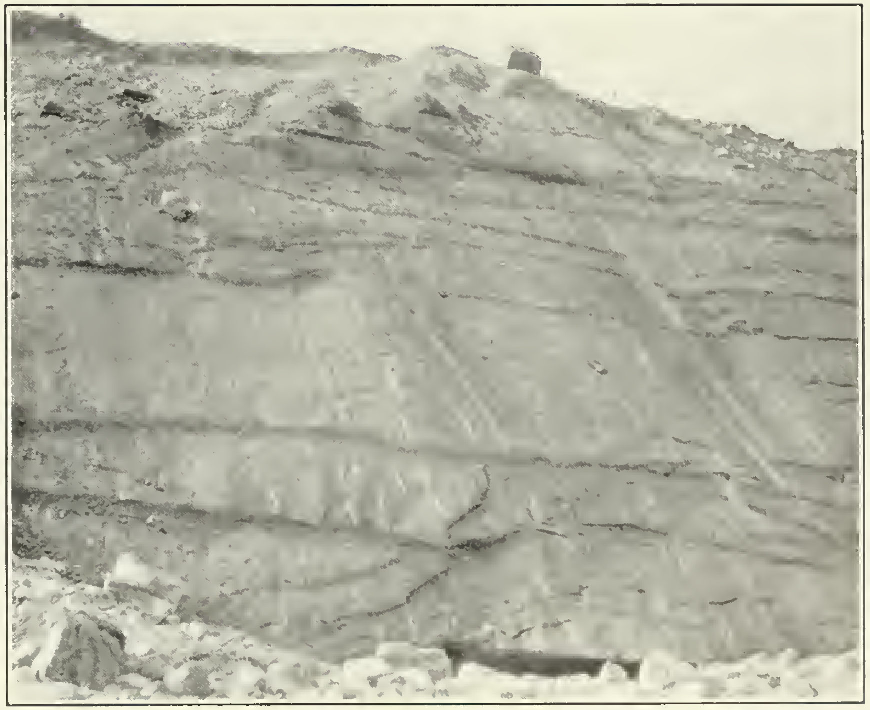


FIG. 4.—Front of Victoria Glacier, showing irregular stratification and shearing. July, 1904.

minimum period of flow. During the spring and fall the flow is very greatly reduced and must be very scant, or nothing, in the winter. Mr. Robert Campbell informs me that he has seen water in the stream, however, beneath the snow and ice of winter.

e. Water temperatures. The temperature of the water at the main exit was found to vary from 32.0° F. to 32.4,° at various times of the day. Near the site of the camp, just outside of the older of the two great block moraines, and some 2,000 feet from the exit, a series of observations was made upon the temperature of the water in the west branch of the drainage brook. The observations were made between July 2 and 27, 1904, and in the early morning, near midday, and in the evening, but not at any stated hours. Most of them were taken between 7 and 8 A.M.; 12 and 2 P.M., and 8 and 9 P.M. Of 56 observations, those for the morning averaged 35.4°, for midday 41.4°, and for the evening 35.2°. A small amount of drainage was received from Mt. Whyte, which must have materially affected the temperatures. Upon July 18, 1904, simultaneous observations were made at the glacier, camp, and at the delta, one mile below. The maximum temperature for the day was 51.7° F. and the minimum 34.8°. The results were as follows:

Time.	Glacier.	Camp.	Delta.
9:00 A.M.	32.4°	35.2°	35.8°
6:00 P.M.	32.4°	34.0°	36.0°

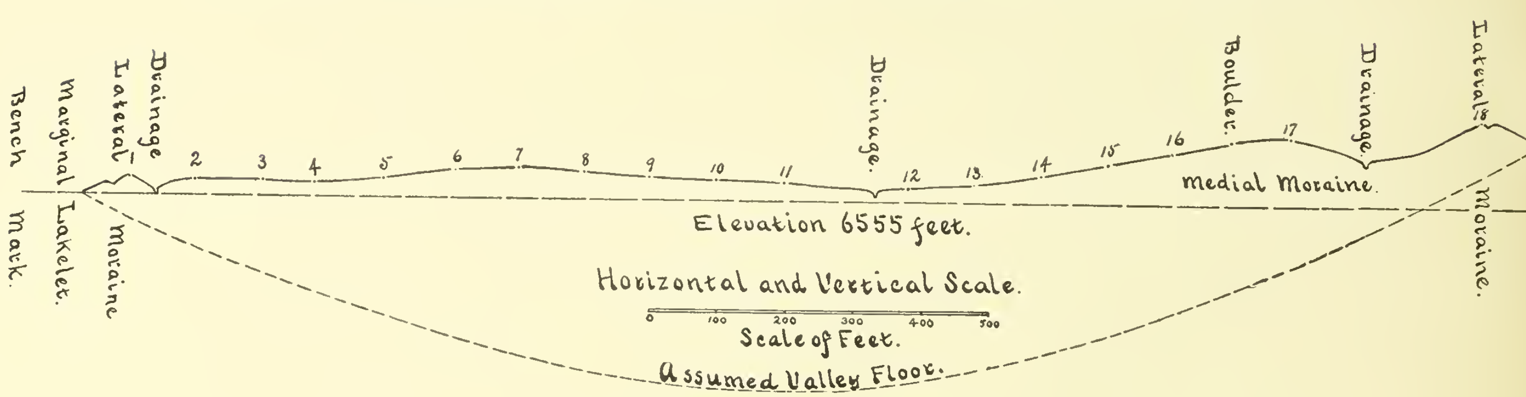
By the time the water has moved across Lake Louise to the foot, its temperature has been raised some 6° to 12°, the temperature ranging from 42° to 48°, during the summer months. The temperature of the Bow River at Laggan, into which Lake Louise is drained, was found to be 54.9° F., Aug. 15, 1904.

5. Forward Movement.

a. Measurements. Long before the attention of scientists was directed to glaciers as suitable subjects for investigation, the Swiss peasants had discovered that they possessed a forward, down-valley movement and that they slowly transported boulders and other objects left upon their surface. In 1841 the Bishop of Annency, M. Rendu, published his remarkable work, *Théorie des Glaciers de la Savoie* (edited by George Forbes, 1874, translated by Alfred Wills), in which he shows a surprising insight into the laws of glacial motion. "Between the Mer de Glace and a river," he writes, "there is a resemblance so complete that it is impossible to find in the latter a circumstance which does not exist in the former" (page 85). Since this was written, in 1839, glacial investigation has done much to justify, if not to actually verify the generalization. Streams of ice and streams of water have many characteristics in common, as well as important differences. All are agreed that the cause of the movement is, in both cases, the force of gravity, acting upon the mass itself, or some other mass in contact with it. As to the nature of the ice movement, those whose opinions should carry the greatest weight are not yet

in agreement. So far as the present investigation is concerned the phenomena observed can be satisfactorily explained only upon the theory that under certain circumstances, and within certain limits, ice is capable of behaving as a plastic body, that is, capable of yielding continuously to stress, without rupture. In the discussion of this property of ice in the closing chapter of this report it is pointed out that the "plasticity" of ice, a crystalline substance, must be thought of as essentially different from that manifested by such amorphous substances as wax or asphaltum.

That the Victoria Glacier is flowing valleyward is capable of direct demonstration. From range lines across the glacier, the Messrs. Vaux marked the position of a certain large boulder July 26, 1899. This was on the portion of the glacier opposite the tributary and back some 6,800 feet from the nose. By July 24, 1900, this boulder was found to have moved forward 147 feet, while a second "near the terminal moraine" was found to have moved 115 feet.[1] So far as may be inferred from the phenomenon of the "dirt bands," to be later described, the former boulder was not in the locus of maximum surface movement, but some 360 feet to the west. In order to gather more definite data concerning the movement of the lower Victoria a line of 18 steel plates was set by means of a transit, the plates being placed as nearly as convenient at an average distance of



100 feet. The line of plates was back 3,600 feet from the nose of the glacier (see map) and was marked by setting the instrument over an established point upon a large block on the shoulder of Mt. Whyte and sighting across to the sharp edge of an easily recognizable cavity in the face of Mt. Aberdeen. The plates were of the style successfully used by the Vaux brothers upon the Illecillewaet Glacier and were $6 \times 6 \times \frac{1}{4}$ inches, with a 9-inch piece of $\frac{3}{4}$ inch gas pipe screwed into the center. They were given two coats of brilliant red paint, were numbered, and had the actual reference line marked in white, after the short piece of pipe had been driven into the ice. An arrow was marked upon each for purposes of orienting, in case they should become turned. In general, where the melting was greatest, it was found that the pipe did not sink into the ice and retain its vertical position, but allowed the plate to drop to one side. The end of

[1] *Proceedings of the Academy of Natural Sciences of Philadelphia*, Mch., 1901, p. 213. "Observations Made in 1900 on Glaciers in British Columbia."

the pipe, however, marked the spot upon the ice over which it had stood, so that its original position could be readily restored (see cross-section). It so happened that the next ten days in the valley were cool and cloudy, with small amounts of rain almost daily. This period was followed by ten days, and more, of bright warm weather, with considerable surface melting. After each of these periods the instrument was set in its former position and the original line again established, but upon ice which had moved down into this position. Measurements were made from this new line to the various plates and the amount of forward movement thus determined. The full data gathered from observations upon this set of plates are shown in table V. The relative vertical position of the plates is shown in the cross-section, as well as their relation to the surface features of the glacier.

TABLE V.

Observations upon the Series of Steel Plates, Set across the Victoria Glacier, July 9, 1904.

(Total Distance across Glacier along line of plates 2,167 feet.)

Station.	Distance from west side.	Elevation above sea-level, July 13, 1904.	Elevation above sea-level, Aug. 4, 1904.	Difference in level in 22 days.	Calculated daily ablation.	Motion for 10 cool days, July 9 to 19, 1904.	Motion for 10 warm days, July 20 to 29, 1904.	Average daily midsummer motion.	Motion for 423 days, July 9, 1904, to Sept. 5, 1905.	Average daily motion for 423 days.	Calculated motion for year.	Estimated thickness of ice.	Remarks.
	Feet.	Feet.	Feet.	Feet.	Inches.	Inches.	Inches.	Inches.	Feet.	Inches.	Feet.	Feet.	
1.	63.4	6585.60	6585.47	0.13	0.068	−0.787	1.181	0.020	0 21	0.006	0.18	62	Crest of left lateral moraine.
2.	163.2	6578.20	6576.11	2.09	1.116	0.394	0.000	0.197	3.00	0.084	2.56	100	Motion irregular.
3.	262.8	6577.74	6576.02	1.72	0.936	0.000	0.000	0.000	....	.....	.....	137	No summer motion. Plate lost in 1905.
4.	342.7	6575.26	6573.04	2.22	1.174	2.953	2.953	0.295	15.70	0.445	13.54	160	Motion for warm period retarded.
5.	443.3	6582.64	6579.89	2.75	1.386	7.874	10.630	0.925	26.10	0.744	22.63	200	Western slope of low crest.
6.	549.9	6595.27	6592.70	2.57	1.231	10.433	17.126	1.378	33.80	0.959	29.17	245	Western slope of low crest.
7.	642.1	6601.22	6599.24	1.98	0.866	11.811	22.835	1.732	47.60	1.350	41.06	275	Crest of low divide.
8.	741.4	6595.36	6593.06	2.30	1.009	12.402	27.362	1.988	56.50	1.603	48.76	292	Eastern slope of low crest.
9.	839.8	6589.06	6586.26	2.80	1.250	18.504	26.378	2.244	51.50	1.460	44.41	302	Eastern slope of low crest.
10.	938.3	6585.02	6582.15	2.87	1.292	18.110	25.984	2.205	72.10	2.045	62.20	306	Eastern slope of low crest.
11.	1037.6	6579.59	6576.65	2.94	1.273	19.882	33.661	2.677	76.30	2.165	65.85	306	Maximum motion for year.
12.	1222.0	6574.49	6570.86	3.63	1.724	18.701	22.638	2.067	74.20	2.105	64.03	287	Lowest plate.
13.	1320.5	6580.91	6577.11	3.80	1.735	18.701	36.024	2.736	74.80	2.122	64.54	276	Maximum summer ablation.
14.	1419.7	6593.45	6590.15	3.30	1.491	16.929	33.071	2.500	71.00	2.014	61.26	262	Gradual slope to medial.
15.	1519.1	6613.69	6611.45	2.24	0.959	10.827	31.693	2.126	67.40	1.912	58.16	252	Gradual slope to medial.
16.	1618.0	6629.03	6627.25	1.78	0.689	14.370	31.299	2.283	63.30	1.795	54.60	236	Gradual slope to medial.
Bldr.	1704.0	6647.90	6646.46	1.44	0.535	11.024	29.528	2.028	58.50	1.660	50.49	220	Boulder on medial moraine.
17.	1791.6	6653.14	6652.03	1.11	0.374	11.614	25.787	1.870	55.50	1.574	47.88	188	Crest of medial moraine.
18.	2083.5	6687.12	6687.15	−0.03	.....	−9.646	4.134	.....	0.17	0.005	0.15	80	Crest of right lateral moraine.

In column 7 is given the total forward movement for the cool period, July 9 to 19, from which the average daily movement can be seen at a glance by shifting

the decimal point one place to the left. The greatest movement was shown by plate 11, almost 20 inches, and this was the plate nearest the centre. From this point the motion diminished very gradually toward the west, but less rapidly eastward, toward the crest of the medial moraine, and then fell off very suddenly. The plates in the crests of the two lateral moraines had moved up-stream, supposedly from the settling of the débris due to ice melting beneath. Plate 3 seemed to be located upon a stagnant portion of ice, showing no movement for either the cool or the warm period, and then could not be found in 1905, apparently because of the side cutting of a surface stream. For the warm period, July 20 to 29, the results are given in the next column for ready comparison. The motion is seen to be greater, almost twice as great for plate 14 and almost three times as great for plate 15. Both plates upon the lateral moraines had moved ahead, although that upon the right lateral had not yet regained its original position. Plate 2 showed no movement whatever for the warm period, and number 4 showed no increase of movement. In column 9 there is given the average daily motion for these 20 days of midsummer, which may be regarded as typical of the season. For this period the greatest forward movement was shown by plate 13, having a daily average of 2.736 inches. It is located some 287 feet east of the centre of the glacier, and, as previously pointed out, showed the maximum ablation. Number 3 showed no movement whatever. On September 5, 1905, the plates were again located, all being readily found except plate 3, and their distances from the original line determined. These results are listed in column 10, from which have been calculated the average daily motion and the motion for a year. In all cases there was a down-stream movement indicated, although very slight for the two lateral moraines. The greatest movement was shown by plate 11, the one nearest the centre of the glacier, amounting to a total of 76.3 feet for the entire period of 423 days, or a daily average of 2.165 inches. This represents a yearly motion of about 66 feet. The central position of the plate of maximum movement for the year was to be expected from the very straight course of this part of the glacier. Its daily motion for the year is about 81 per cent. of its midsummer motion, which means that for the greater part of the year the movement is fairly uniform. The table suggests that during the season of maximum motion there are cross-currents set up in the ice, and, with reference to the body of the ice itself, not the bed, even back currents. During the year, however, the impulse is steadily and regularly forward. Studies upon the dirt bands of Forbes, to be later discussed, indicate that as we approach the steeper ice slope opposite Lefroy, the motion is more rapid than that given in the table.

b. Frontal changes. The rate of melting about the nose and side of the glacier, in connection with the rate of forward movement of the ice, determines the behavior of the front. When these two factors are balanced the glacier appears to halt, and, if carrying débris, begins to build a terminal moraine. If either the rate of forward movement, or the rate of recession from melting, is in excess then the glacial extremity advances, or retreats, entirely regardless of the

fact that the ice of the glacier is continually moving forward. Owing to the rock veneer which completely covers the nose of Victoria, the amount of melting even during midsummer is very small. The last episode here was one of advance, the glacier having extended itself, some decades ago, into a forest of spruce and fir and checked its own advance by mounting a heavy moraine of rock fragments which it was incapable of pushing aside (plate v, figure 1). The cut stumps and broken trunks which lie about the nose, some of them entirely out of reach of the present glacier, appear to have been produced by an avalanche from between Mt. Aberdeen and Castle Crags, which encircled the nose when it stood somewhat farther back than at present. Trees now growing in the path of this avalanche are 28.3 inches in circumference and by calculation should be 130 years old. In order to determine how the nose was behaving, three accurate measurements were made with a steel tape between definite points upon coarse blocks of the old moraine and upon others that seemed rather firmly embedded in the frontal slope. Between July 9 and September 13, 1904, in all 66 days, each of the latter blocks had settled back approximately an inch, presumably owing to the wastage of the ice beneath from melting. Confirmatory evidence that such melting was in progress was furnished by a small *clear* stream of water at 32°, which escaped through the rocks just west of the nose. Between September 13, 1904, and September 2, 1905, when measurements were again made, this small recession was partially made up, but the blocks still lacked .36 in. to .72 in. of regaining their former position. With the front so delicately poised it is evident that a very small additional impulse from behind would inaugurate an advance.

At a point 2,000 feet up from the real nose, at about the middle of the oblique ice front already noted, there lies a large red quartzite boulder, which was used by the Messrs. Vaux as a reference block. This is the largest of the three blocks in the middle foreground of plate x, figure 3, as it appeared in August, 1903. This boulder was observed protruding from the ice, a little over half-way up the face, in the midsummer of 1898, by Prof. Charles E. Fay. In this position it was photographed by him, and also a week later, when it had fallen. Plate x, figure 2, shows the boulder in position in the ice. In 1899, July 26, this boulder was found by the Messrs Vaux to be 20 feet from the ice front. How much of this 20 feet was due to recession and how much to the rolling or bounding of the block in falling, cannot now be determined. On July 24, 1900, the boulder was found to be 26 feet from the ice, indicating a recession of 6 feet for the year. August 23, 1903, the block was found by the writer to be 76 feet from the ice foot, giving an average recession since 1899 of 14 feet. The following July the block was marked with bright red paint, so that it could be readily located by others: "A. Ice foot 74.5 ft. 7/23/'04. Sr." The elevation of a line upon the face, determined by spirit level from Lake Louise as a base, was recorded as 6,264 feet[1] above sea-level. When compared with the distance noted above for the previous

[1] This elevation was based upon 5,675 feet for the height of Lake Louise above sea-level. The corrected elevation as now given by the Canadian Topographic Survey is 5,670 feet, or five feet lower.

year this would indicate an advance, whereas the glacier was actually in retreat. The necessity of taking the measurements as nearly as possible at the same corresponding time in the season becomes evident. In 1904 measurements were also made August 4 and September 13, giving distances of 76 and 86.45 feet respectively. If we assume a *uniform* recession between these last two dates we have a daily amount of 0.26 feet and for the interval between August 4 and August 23, at which date the measurement was made in 1903, an additional recession of 4.94 feet. This amount, added to that of August 4, gives 80.94 feet, and the approximate recession from August 23, 1903, to August 23, 1904, was 5 feet. In 1905 the measurements were made September 2, and gave a distance of 106.8 feet from the reference block to the ice foot. This means a recession of about 25 feet for the year 1904–5. For the series of six years 1899 to 1905 the total amount of recession observed at this point was 86.8 feet, or an average of 14.5 feet annually. The following summary for this boulder may be given:

1898.	Fell from ice early in August.
1899.	20 feet from ice foot.
1899–1900.	Ice receded 6 feet.
1900–1903.	Average recession of 19 feet.
1903–1904.	Ice receded 5 feet.
1904–1905.	Ice receded 25 feet.
1899 to 1905.	Average recession 14.5 feet.

About 375 feet nearer the nose a second block was selected for reference and upon July 23, 1904, marked "B. To ice 38.5 ft. 7/23/'04. Sr." Between this date and August 4, 1904, the recession amounted to 3.9 feet and up to September 13 equalled 11.5 feet. The distance from the block to the ice foot was again measured September 2, 1905, and amounted to 63.2 feet, indicating a recession between September 13, 1904, and the latter date of 24.7 feet. Calculated, as above, for the year September 2, 1904, to September 2, 1905, the recession was approximately 15 feet. Since the exposure of the ice face opposite blocks A and B is so nearly uniform, we may assume safely that the rate of melting upon the oblique face is substantially the same at the two points of reference. The diminished recession of the ice at B would then indicate that the forward movement of the layers here must be greater than at A. From data already cited it is seen that the forward movement at the nose is insignificant and it appears that the main current of ice, as it approaches the nose, is deflected to the westward and that the oblique ice wall is in reality part of the *front*.

c. Shearing. The steeply inclined ice front, having a slope of 46°, near reference block B, shows a succession of ice strata, more or less well defined, which dip back into the glacier at a rather steep angle. At the mouth of the abandoned drainage tunnel (plate VIII, figure 4, and plate XII, figure 3), these strata in 1904 had a dip of 26°, which is below the actual dip. Between these strata there is dust, sand, a little fine gravel, and, occasionally, a cobble-stone, but the amount of foreign matter is small and inconspicuous. A few consecutive days' visits to this

part of the glacier, in early July, showed that a differential movement between adjacent strata seemed to be taking place (plate x, figure 4), the upper layers being pushed beyond the lower. There was not enough foreign matter in the layers to explain the phenomenon by differential melting. In the case of the South Point and other Greenland glaciers Prof. T. C. Chamberlin observed a jutting of the upper stratum which was apparently due to the more rapid melting of the under layer, owing to its heavier load of dark-colored débris and consequent more rapid absorption of the sun's heat. Upon the same glacier, however, he found very conclusive evidence that the upper stratum may be pushed bodily over the lower, giving rise to a shearing action between the adjacent strata.[1] In August, 1903, Prof. I. C. Russell found a similar phenomenon on one of the small glaciers visited on the Three Sisters, Oregon. In this case he thought the evidence conclusive that the jutting of the upper stratum was due to differential melting.[2] In order to ascertain whether or not this was a similar case of shearing, a place was selected 50 to 52 feet above the base of the ice and heavy spikes driven into the ice until their heads were flush with the surface. Three were placed in the base of the upper stratum, about three feet thick, and three corresponding ones in the upper part of the subjacent layer, which had a thickness of about two feet. July 21 the upper layer projected beyond the lower 19.7 inches at the place selected for observation. Two days later it was evident that the melting was greater upon the upper layer, in spite of which it now projected 24.4 inches beyond the lower. The spikes were now visited regularly for 10 days, July 25 to August 3, the amount of melting measured, as well as the amount of projection of the two layers, and the spikes reset. These measurements were necessarily rough, but they showed each day that the melting was greater upon the upper stratum, the average amount for each spike being 1.76 inches, while that for the lower stratum was 1.53 inches, or nearly $\frac{1}{4}$ inch less. Some sand and fine gravel, washed down from above, daily accumulated in the lee of the projecting upper layer and gave the appearance of a concentration of dirt in the upper part of the lower stratum. When this dirt was small in amount it was observed that melting was accelerated; when greater in amount, that the melting was retarded. The upper stratum continued to gain slowly, but irregularly; reached a maximum of 26.6 inches and closed at 25.6 inches, or about 6 inches more than at the beginning of the observations. The results are tabulated below for inspection. Time did not permit the verification of the results at other points where the same thing appeared to be taking place, but there seemed to be no question that the upper layer was moving bodily over the lower. This movement represents a shearing of the body of the glacier, the shearing-plane lying between the adjacent strata, but not a shearing of the ice itself. Knowing how readily iron absorbs heat it may be supposed that six-inch spikes might induce melting sufficiently to render their use unsatisfactory. Lying in the ice horizontally there was considerable melting about the outer half of the spike, allowing it to sag and slide

[1] *Journal of Geology*, vol. III, 1895, p. 676.

[2] "Glacier Cornices," *Journal of Geology*, vol. XI, 1903, p. 783.

forward, but they did not seem to penetrate the ice any by such action. But even if such an effect was produced to an appreciable extent, it would have been more pronounced upon the upper row of spikes, which received more sun's heat owing to their more exposed position, and the actual melting upon the upper layer would have been still greater than is indicated in the table. Although the purpose of the experiment was to ascertain the differential melting, rather

TABLE VI.

Shearing Observations, Victoria Ice Front.

Date.	Upper stratum.			Lower stratum.			Projection of upper layer beyond lower.	Temperature.		Remarks.
July 23	Melting about spikes.			Melting about spikes.				Max.	Min.	
July 25	2.75 in.	2.00 in.	2.50 in.	1.50 in.	2.25 in.	2.25 in.	25.2 in.	60.7°F.	35.0° F.	Cloudy.
" 26	2.00	2.06	2.25	1.25	2.25	2.25	25.0	55.2°	40.0°	Warm.
" 27	2.37	2.56	2.37	1.25	3.37	2.25	26.6	68.4°	38.8°	Warm and bright.
" 28	3.25	2.56	2.50	2.75	2.25	2.38	25.6	69.7°	45.4°	Very warm.
" 29	1.62	1.56	1.38	1.19	1.50	1.87	24.6	74.0°	45.5°	Cloudy.
" 30	0.87	0.69	1.25	0.94	0.75	1.06	25.0	74.0°	36.2°	Cool and cloudy.
" 31	1.75	1.19	1.00	1.00	1.06	1.44	26.4	50.4°	38.0°	Mostly cloudy.
August 1	1.50	1.63	2.00	1.63	1.38	1.50	26.2			Bright.
" 2	2.31	2.00	2.38	1.50	1.50	1.75	25.0			Bright.
" 3	2.00	2.12	1.50	1.38	1.62	1.56	25.6			Bright and warm.
10 days' obs.	Average melting 1.76 in.			Average melting 1.53 in.			Increase 5.9 in. since July 21.			

than the actual, it is interesting to compare the maximum average daily effect here observed with the maximum melting observed upon the surface of the glacier, where least protected by débris. See table v, column 6, plate 13, page 31.

d. Crevasses. The general forward movement of the ice, and its inability to adjust itself to inequalities in its bed, give rise to systems of cracks, or crevasses. These show that the limit of tensional strain, without rupture, has been exceeded in this part of the ice. They occur in all parts of the glacier from the bergschrund to the very nose, and when insecurely covered with snow, they form the greatest menace to glacial exploration. The inexperienced cannot be too strongly cautioned against the danger arising from these concealed traps, against which the judgment of best trained Swiss guides is sometimes pitted in vain. In passing from one portion of its bed to a sufficiently steeper slope, as that opposite the nose of Mt. Lefroy, v-shaped cracks in the ice occur, extending directly across the glacier. They penetrate to considerable depths into the ice, as measured in feet, but their depth, compared with the total thickness of the ice, is probably small, unless the change in the inclination of the bed is very abrupt, when they may reach the bed of the glacier. When these transverse crevasses have an east-west trend, the sun's rays strike the northern lip of the crevasse more strongly than the southern and, in the course of the season, it becomes more rounded. In passing down the slope the crevasse walls come together and the crevasse is healed, except for the slight depression caused by the greater melting upon the

northern crevasse wall. It is into this depression, which becomes convex down-stream owing to the more rapid central movement, that fine débris may collect and give rise to the "dirt bands" of Forbes, to be presently described. As the glacier rounds Lefroy and enters a broader portion of its valley, it has a chance to spread laterally, and longtitudinal and somewhat radiating crevasses are opened which may intersect those having the transverse position. If the glacier is again contracted these crevasses will also be closed, and if any depression is left, it will slope down-stream and not have a tendency to collect débris.

The more rapid movement of the middle portion of the glacier, when compared with the sides, which are retarded by the friction of the valley walls, induces tensional strains between the central and marginal masses. In consequence, along the sides, there is opened up a characteristic system of marginal crevasses at right angles to the resultant strain. These extend inward and upward, making, theoretically, with the sides angles of about 45°. The difference between the central and marginal flow must reach a certain value, and be sufficiently abrupt, otherwise the ice seems capable of yielding without rupture. In this way we may account for the absence of marginal crevasses over the lower west side of the Victoria. The very sudden change in movement, shown in table v, between the margin and the ice of the near-by medial moraine, plates 18 and 17, is evidently responsible for the series of marginal crevasses that are seen between the line of plates and the tributary (see plate III). From their absence upon this side, farther down, we infer that the ice beneath the medial moraine becomes more sluggish as the main flow is deflected westward. Opposite Mt. Lefroy conditions are favorable for their formation and they are well represented upon either side. Opposite the tributary they do not occur, as the marginal ice is sufficiently yielding. Upon the tributary itself these crevasses are well represented, except over the collecting area for the Lefroy. After their formation their inner ends may be swung around until they assume a transverse, or even reversed, position, as seen upon the Aberdeen side of the Lefroy. Here we find one series, averaging N. 51° E. and making angles of about 66° with the margin but ranging from 52° to 86°; and a second series, many of them nearly closed, and apparently older than the preceding, having an average direction of N. 95° E. and making with the side angles of about 111°.

The size of many crevasses in the spring and their contents of fresh snow show that they may persist through a series of seasons. Sometimes they become partially filled with water which may melt out cavities in their walls and give rise to the most exquisite ice grottoes, a peep into which is worth miles of travel. The closing of crevasses sometimes confines pools of water, often under hydrostatic, or ice pressure, and as the surface of the ice is lowered by melting, the water suddenly bursts forth with geyser-like action. The compression of air enclosed in cavities, or brought in by surface streams, often gives rise to a bubbling at the surface and a faint hissing, or chirping sound—the "sighing" of the glacier.

CHAPTER III.

VICTORIA GLACIER (*Continued*).

1. Glacial Structure.

a. Stratification. In this chapter there is set off for description a number of features, especially well shown upon the Victoria and its tributary the Lefroy, but which were more or less well represented upon the other glaciers also and are characteristic of glaciers in general. Among the first of these is the stratification the origin of which in the névé has been given on page 22. It is conceivable that a stratification in the basal layers might arise exceptionally through the operation of differential stresses in the body of an unstratified glacier. As pointed out by Chamberlin in the case of the massive Greenland glaciers shearing-planes may thus arise leading to a concentration of débris. The lower stratum over which the shearing takes place may be protected from the shearing thrust, may be more heavily charged with débris, or may be more rigid because of its temperature and water content.[1] In the case of the Canadian glaciers studied it seems probable that the strata are depositional, in very large part, at least. Conditions most favorable for the formation of shearing-planes would seem to be found in the case of the Illecillewaet Glacier, owing to the body of ice and its rapid descent from its reservoir. The depositional stratification is almost completely obliterated by the ice cascade and none other has arisen to take its place.

The stratification of the Victoria continues throughout the glacier's extent, and is seen at the oblique front, in the drainage tunnels and channels, in the moulins, and upon the walls of the crevasses. The line of demarcation between adjacent strata is usually only a soiled streak, but sometimes there is sand, gravel, and an occasional cobble-stone. The strata vary in thickness from 12 inches to 10 or 12 feet, as seen upon the Lefroy. This thickness would indicate that 9 to 110 feet of loose snow had taken part in their formation. The average thickness of the Victoria strata is not too great to suppose that they may represent the accumulated and compacted snow fall of the year. Those of unusual thickness are to be ascribed to avalanches. About the mouth of the abandoned drainage tunnel in 1904 the stratification of the ice was well displayed (plate VIII, figure 4, and plate XII, figure 3) as previously referred to. Three strata here averaged 26 inches, the full thickness of the lower one not being seen. The uppermost layer was wedge-shaped and thickened from 13 inches to 81 inches. The strata all dipped back into the body of the glacier at an average angle of 26°, as measured upon the tunnel walls, but this was less than the actual angle when measured at right angles to the strike of the layers. The irregularities shown in the strata here, as well as in the oblique ice face, are probably due to the partial nourishment of the glacier by means of avalanches of snow and ice. Upon the regenerated Lefroy Glacier the strata are massive, 6 to 12 feet in thickness, having been produced entirely from the avalanches from Mt. Lefroy. These strata all dip towards the

[1] See *Geology*, vol. 1, Chamberlin and Salisbury, p. 303.

FIG. 1.—Line of contact between two "dirt zones," Lefroy Glacier. These zones represent outcropping edges of depositional strata.

Aberdeen. Mitre.

FIG. 2.—"Dirt zones" upon Lefroy Glacier, frequently confused with "dirt bands" of Forbes. Compare figure 2, plate XVI.

region of accumulation, directly beneath the front of the hanging glacier. In the lower part of the glacier this dip averages 22°, ranging from 12° to 26°, while farther up-stream the dip is more gentle, only 5° to 10°, as well seen in the crevasse walls. The Mitre Glacier, near the junction of its two feeding streams, is crevassed and faulted and displays a very regular stratification (plate VII, figure 2).

b. Dirt zones. Upon a moderately steep slope, such as is found upon the lower Lefroy, the outcropping edges of the strata, somewhat differently charged with débris, give rise to broad contrasting zones which pass evenly and symmetrically around the slope. As generally seen these bands are convex in the direction of flow, but irregularities in the surface slope of the ice, or in the angles at which the strata come to the surface, may make them concave down-stream for portions, at least, of their course (plate XI, figure 2). The upper edge of one zone upon the Lefroy contrasts very strongly with the adjacent layer, as shown in plate IV, figure 2. It was the abnormal position of this line, first seen from the Devil's Thumb, that furnished the clue needed to decipher the relation of the Lefroy to the Mitre Glacier. A nearer view of this zone line, and two adjacent ones, is shown in plate VIII, figure 1, and a still nearer view in plate XI, figure 1. Because of the irregularity and small size of the strata, as well as the débris covering, the phenomenon is not well seen upon the Victoria. At the place where it should show the best it is, furthermore, obscured by the dirt bands of Forbes, with which the zones are often confused. These two features are so different in origin and significance, yet often so similar in appearance, that they should be sharply separated in the field and in descriptions of glaciers. Plate IV, figure 2 shows the dirt zones, upon the Lefroy, at the left, and the dirt bands, upon the Victoria, in the middle foreground.

c. Granular structure. A lump of ice from the body of a stratum, which has not yet begun to show any signs of melting, is compact, firm, brittle, without cleavage, and beautifully blue by transmitted light. It appears quite homogeneous, except for the presence of air spaces, which may be sparingly and irregularly scattered through the ice, or they may be arranged in seams, to be presently described. Under the polariscope, in thin slices, the ice is seen to be crystalline in structure and made up of closely pressed polyhedrons, ranging in size from hazel nuts to goose eggs. These polyhedrons are the so-called glacial granules, that may be traced back to the névé, growing smaller and smaller, upon an average, as we recede from the nose. They fit tightly together, interlocking perfectly, have curved rather than plane faces, and show no spaces nor signs of any cementing material between the individual granules. There seemed to be a correspondence between the size of the glacier and the size of the granules seen about the nose, the largest granules being observed in the Illecillewaet and Yoho glaciers, in the case of the latter ranging from 0.2 inch to 2.75 inches and averaging about one inch. From the fact that such granules occur in no other form of ice, that they may be traced back to the névé, becoming smaller and smaller and more numerous, the inference is reasonable that, in some way, these granules

must be derived from those pellets which constitute the typical névé. The question as to how the granules are developed at once arises, but cannot be yet answered with certainty. (For a fuller discussion of this subject see page 127). That the larger are not produced by the simple freezing together of a certain number of the smaller pellets is shown by the fact that each mature granule is crystallographically homogeneous. Those who have written most recently upon the subject hold the view that the granules are permitted to grow by a process of partial melting and refreezing, the larger thus appropriating to themselves the water derived from the melting of the smaller. Mügge holds that this melting takes place at the outer limits of the individual granules because of the constant readjustment of pressures within the body of the glacier,[1] and in this change of the granules he sees the cause of glacial motion. Chamberlin believes that a similar change occurs because of differential stresses upon the granules undergoing constant adjustment, assisted by whatever heat energy may be conducted into the glacier from above.[2] Drygalski recently argues in favor of a melting of the granule by pressure both internally and at its outer surfaces, by which some granules may be completely liquified and subsequently refrozen.[3] Upon this action he bases his theory of glacial motion and the orientation of the granules about the nose, as brought out in his Greenland report in 1897 cited below.

Experiments of Hagenbach-Bischoff in 1883 showed that when two ice crystals, having differently directed axes, are pressed together they unite without melting into a single crystal, "the larger eating up the smaller." The union differs from the regelation of Tyndall in that there is a rearrangement of the molecules by which the resultant crystal is crystallographically and optically homogeneous. To distinguish it from the method of granular growth due to melting and refreezing it is spoken of as a "dry union." This principle applied to the glacier would lead to a continual reduction in the number of granules and a corresponding increase in their size, as pointed out by Hagenbach-Bischoff, Heim, and Emden. It will be shown later (page 128) that this theory of granular growth seems to the writer to best explain the remarkably perfect preservation of the often delicate laminæ and blue bands seen about the nose and sides of the glacier. Combined with the special type of plasticity exhibited by ice crystals this method of perfect dry welding may explain the absence of noticeable distortion of the ice granules, which, as urged by Chamberlin, should be observed in the direction of flow if the glacier moves because of its viscosity.

In order to determine whether or not there was any tendency towards the orientation of the granules in the basal layers about the nose, thin slabs of ice

[1] "Weitere Versuche über die Translationsfähigkeit des Eises, nebst Bemerkungen über die Bedeutung der Structur des grönländischen Inlandeises," *Neues Jahrbuch für Min., Geol., und Pal.*, 1900, Bd. II, S. 87 zu 98.

[2] "Recent Glacial Studies in Greenland," Presidential Address before the Geological Society of America, *Bull. Geol. Soc.*, vol. 6, 1895, p. 211; "A Contribution to the Theory of Glacial Motion," Decennial Publications of the University of Chicago, vol. IX, 1904, pp. 10 and 11; *Geology*, by Chamberlin and Salisbury vol. I, 1904, pp. 299 to 306.

[3] "Ueber die Structur des grönländischen Inlandeises und ihre Bedeutung für die Theorie der Gletscherbewegung," *Neues Jahrbuch für Min., Geol., und Pal.*, 1900, Bd. I., S. 71 zu 86.

FIG. 1.—Glacier capillaries, Yoho Glacier, outlining glacial granules. Much reduced in size.

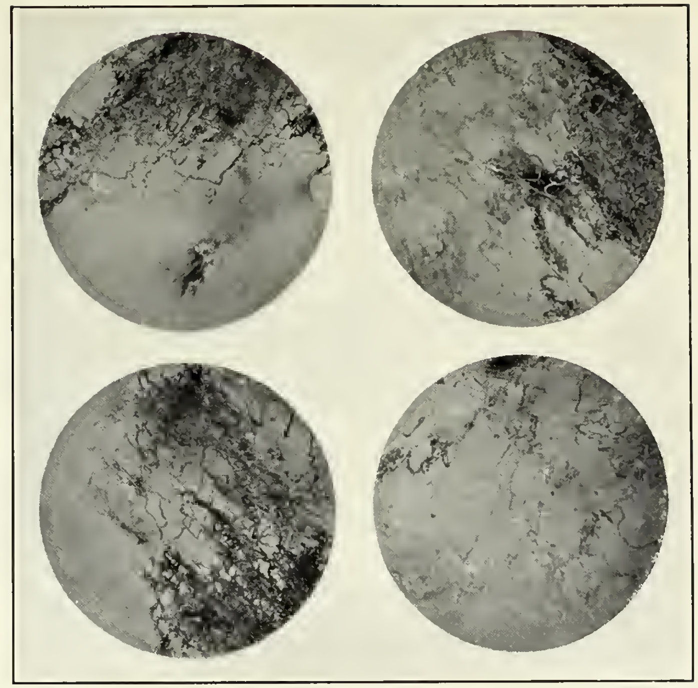


FIG. 2.—Glacier capillaries, infiltrated, Illecillewaet Glacier. Much reduced in size.

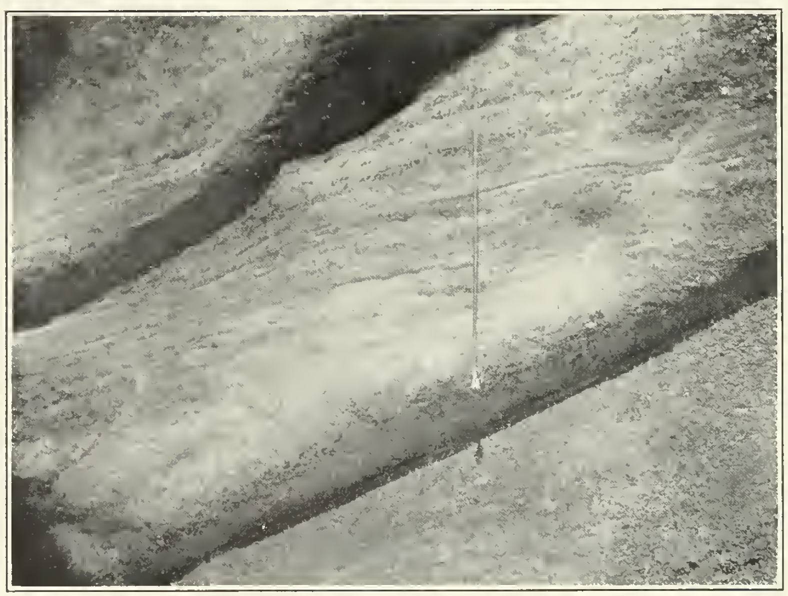


FIG. 3.—Stratification upon wall of ice tunnel, Victoria Glacier, July, 1904. Steel tape run out to 50 cm. Observe glacial granules and blue bands and note unconformity of latter with strata.

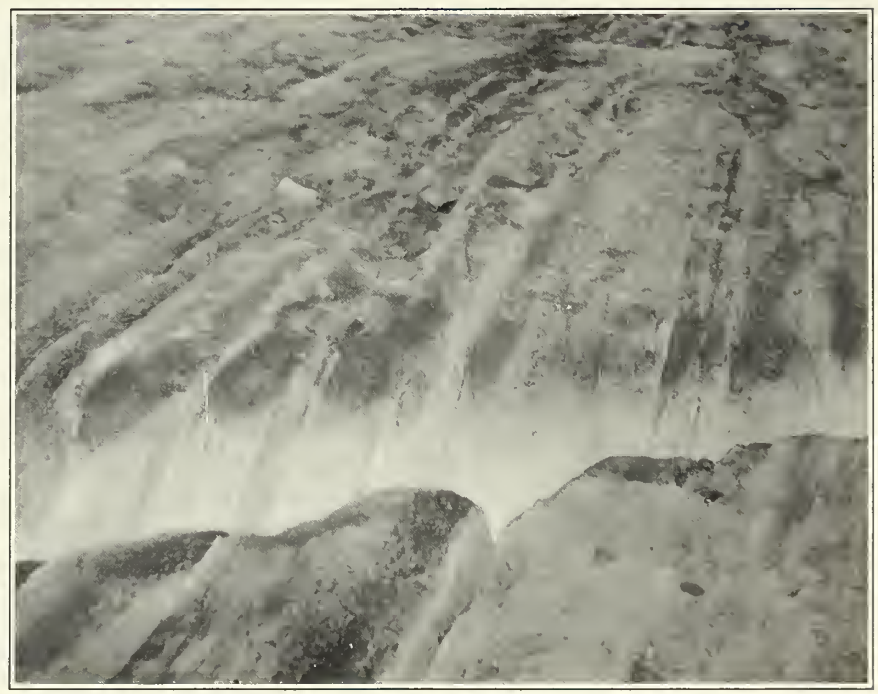


FIG. 4.—Blue bands seen in upper part of Lefroy Glacier, cutting strata at high angle. A perfect example of a regenerated glacier.

were sawed out in various directions and melted down to thin slices by rubbing them over the face of a warm saw-blade. Examining these sections with the polariscope, it was found that in the case of those cut horizontally from the glacier, from $\frac{1}{4}$ to $\frac{1}{3}$ of the granules remained dark when revolved. In the case of sections cut vertically, either across or lengthwise of the glacier, only an occasional granule was found to show this phenomenon. From this it appears that there is a tendency towards the orientation of the granules near the lower portions of the Victoria, Yoho, and Illecillewaet glaciers, a considerable percentage of the granules having their main optic axes in a vertical position. The same phenomenon was observed by Drygalski in the case of the Greenland glaciers.[1]

d. Capillary structure. When glacial ice is subjected to a moderate melting temperature for a sufficient length of time there is developed a network of capillary tubes, at the junctions of three or more granules. These tubes are approximately circular in cross-section and from 0.008 inch to 0.04 inch in diameter. Their walls reflect the light strongly and give the appearance of silver threads, more or less perfectly outlining the granules. From the ease with which liquids course through the tubes one infers that they are free from or contain but little air. From beneath the margin of the Yoho Glacier it was possible to get some of them upon the camera-plate, although, many of them being out of focus, they all appear disconnected (plate XII, figure 1). By making a strong solution of potassium permanganate and placing it in a basin hollowed in the ice, the capillaries were in a few minutes beautifully infiltrated, the red solution contrasting strongly with the rich blue ice (plate XII, figure 2). Upon the faces of crevasse walls, and in the drainage tunnels, where the sides are smoothed by melting, these tubes may be seen in longitudinal section, forming a pattern by which the irregular granules are outlined. These are the tubes which Agassiz and Forbes found in the Alpine glaciers, but which Huxley and Tyndall did not discover. Agassiz was in error in supposing the entire body of the glacier to be permeated with such a system of capillary tubes and Huxley in denying that any part of it was.

e. Melting features. As melting proceeds the capillaries become larger; irregular, "crinkly" spaces are opened between the faces of adjoining granules, and the delicate network is gradually obliterated, as shown in portions of plate XII, figure 2. With this increased reflecting surface the ice loses its deep blue color, becomes whiter, and when the granules are small it assumes somewhat the appearance of névé. A slight pressure now, or a sharp blow, will cause the ice to crumble into its component granules. These granules are shown, but rather indistinctly, in plate XII, figure 3. While still in position, as well as after they have fallen apart, the granules are seen to be covered completely with delicate parallel ridges and rows of fine points winding over the surface and having no definite direction with reference to the crystal. The ridges and rows of points are about 0.04 inch distant, but show some variation, and form a complicated pattern that is different for each granule, suggesting more strongly than anything else the ridges seen upon the inside of one's finger-tips. This phenomenon

[1] *Grönland-Expedition der Gesellschaft für Erdkunde zu Berlin, 1891–93*, Bd. I, 1897, S. 494.

was noted by Drygalski in the granules of the Greenland glaciers and described briefly upon page 488 of his report cited. It had been previously observed and described by Emden in his paper *Über das Gletscherkorn*, p. 22, figure 5, and designated as melting water curves. While neighboring granules were in position, no correspondence could be made out between the ridges and furrows of adjoining faces. An attempt was made to take impressions of the markings but no suitable material was at hand. The wall preparation "alabastine" reproduced perfectly the finger markings, but refused to work with a wet ice surface. The "stripes of Forel" are delicate ridges, passing around the granules at right angles to the main optic axis, and evidently connected with the intimate crystalline structure of the crystal. They mark the edges of the very fine plates of which each ice crystal is composed, placed together with their flat faces perpendicular to the main optic axis. The ridges here described are entirely different and do not suggest to the writer any possible explanation. They are certainly due to the manner of surface melting but it is far from apparent what could give rise to such a pattern. In the prisms of lake ice Emden found both the melting curves and Forel's striping present, with an intermediate type of ribbing, and concluded that all three were due to one and the same cause and independent of the structure of the crystal (p. 24).

Granules that have been well acted upon by the sun show a system of very flat, circular disks, all with their planes parallel and at right angles to the main optic axis. These were first observed and figured by Agassiz in his *Système Glaciaire*, 1847 (plate VI, figures 7 and 10) and described also in his *Geological Sketches*, vol. I, p. 275. They were believed by him to be air bubbles, flattened by pressure, although observed to lie differently in adjoining granules. These are now known as "Tyndall's melting figures," described in his *Glaciers of the Alps*, Ed. 1896, pp. 353 to 361. They represent "vacuous space," left in the ice by the contraction of the water when changed from its solid to its liquid condition, the melting planes coinciding with the crystalline plates, of which the granule appears to be composed. They are thus serviceable in enabling one to determine the direction of the main axis of each granule, but there were not enough of them seen at one time about the nose of the glaciers to settle the question of the orientation of the granules.

f. Blue bands. Many observations were made upon the blue bands, of which the strata are generally composed, with the hope of shedding some light upon their position and direction in the ice and their relations to the strata. In general, they were found well developed about the nose and along the sides of the glaciers, well up toward the névé region. The lower Victoria has too much débris covering to enable them to be well seen at the surface, but in the tunnels and moulins and along the walls of the surface streams they are to be seen in a good state of development. At the mouth of the tunnel they were found to average 0.59 inch to 0.75 inch and to dip back into the glacier at an average angle of 9°, while the average slope of the strata was 26°. This unconformity of the laminæ and strata is well shown in plate XII, figure 3, although the laminæ

become indistinct in proportion as the granules separate. In the moulins, opposite the oblique ice face the average inclination up-stream was found to be 30°. Under the medial moraine, near the nose of Mt. Lefroy, the bands were longitudinal, vertical near the centre but radiating, fan-like, upon either side; the outer ones inclining as much as 45°. Although for over 65 years the subject of study, we are not much nearer an explanation of this common glacial feature than when first observed in 1814 by Brewster. The idea of Forbes that they represent ice-filled crevasses, or shearing-planes, has been generally abandoned. The early view of Agassiz, that they represent the original lamination of the névé snow, successively compacted by rain or melting, and then frozen (*Geological Sketches*, p. 247), has been revived by Reid[1] and Hess.[2] Crammer accepts this same view of the origin of these bands, and argues further that they represent shearing-planes along which the motion of the glacier proceeds.[3] In his prize essay, *Über das Gletscherkorn*, p. 37, Emden advances the theory that these blue bands were formed by the overflow from glacial brooks, infiltrated and frozen. The view of Tyndall, that these blue bands result from pressure and, when formed, are at right angles to it, had received very general acceptance. In the former view the lamination is to be regarded as an organic part of the glacier; in the latter, the banding is of secondary origin, and might not be present at all, under certain circumstances. Tyndall's theory is set forth clearly in his *Glaciers of the Alps*, chapter 31, and is summarized thus: "The ice of the glacier must undoubtedly be liquified to some extent by the tremendous pressure to which it is here subjected. Surfaces of discontinuity will in all probability be formed, which facilitate the escape of the imprisoned air. The small quantity of water produced will be partly imbibed by the adjacent porous ice, and will be refrozen when relieved from the pressure. This action, associated with that ascribed to pressure in the last section, appears to me to furnish a complete physical explanation of the laminated structure of glacier-ice."

The Lefroy Glacier, being a regenerated and at the same time a parasitic one, moving in a different direction from its host, furnishes an opportunity for testing our two theories. In plunging 2,000 feet into the valley all traces of the original stratification and lamination of the névé must be destroyed. Since the avalanches of snow and ice occur only, or mainly, during a few months of the year, it may be safely granted that layers of this material will be spread out, more or less unevenly, about the base of the cliff, alternating probably with layers of snow which falls directly into the valley, or is in part drifted there. The result of this action will be to restore the stratification seen in the hanging glacier at the crest of the precipice. It cannot be assumed, however, that anything like the original lamination of the ice can be reproduced. Possibly around the margin of the area covered by the avalanches, there might be built up a succession of

[1] "The Relation of the Blue Veins of Glaciers to the Stratification," *Comptes Rendus IX. Congrès Geol. Internat. de Vienne*, 1903, pp. 703 to 706.

[2] *Die Gletscher*, 1904, p. 175.

[3] *Eis- und Gletscherstudien. Neues Jahrbuch für Min., Geol., und Pal.*, XVIII. *Beilage-Band*, 1904, pp. 105 and 106.

fine layers, but such a deposit would be of limited thickness since it would very soon be pushed outward and beyond the reach of the snow dust. The bulk of the avalanched ice would come down in great heaps, which could show neither original nor acquired lamination. Granting that some of the avalanched snow and ice would become finely stratified, we would expect it to alternate with much more that was not, and with frequent layers, produced by the direct snowfall into the valley, showing the typical névé lamination. Furthermore, the position of the Lefroy upon the Mitre is such that these laminæ along the sides of the former, as well as over the surface, should run across the valley and should be entirely conformable with the strata.

Upon the other hand if the banding is of secondary origin and the result of pressure against the valley walls, it should be entirely similar in adjacent strata of the same character, exactly as found in ordinary glaciers not formed as is the Lefroy, should be found near the sides of the valley and parallel with them, and should show an utter disregard for the position of the Lefroy strata. In ascending the Lefroy to apply our test we find a beautifully perfect and typical banding upon the Aberdeen side, well shown upon the crevasse walls, under the lateral moraine. The inclination of the blue bands is very steep, ranging from 72° to 90° and averaging 83°, as they dip downwards and into the body of the glacier. These bands are continuous across the gently inclined strata and cut them at a high angle. Plate XII, figure 4, shows the perfectly developed bands, the margin of the glacier lying to the right, but does not give the desired view of the strata. Toward the centre of the Lefroy these bands become obscure at the surface, or disappear entirely, but are found again upon the Lefroy side, between the collecting region and the nose of Mt. Lefroy. So far as this feature is concerned the Mitre and Lefroy seem to be a unit and the evidence is all in favor of the pressure theory.

Near the nose of the Illecillewaet Glacier the blue band structure is very perfectly shown about the sides, as seen in plate XIII, figure 1. There is no lateral pressure upon either side and the bands conform with the valley floor. Furthermore, they would be conformable with the strata, providing the latter were present, but these have been destroyed, presumably at the ice cascade farther up the slope. It may be maintained that at such a cascade it is only the superficial layers that are disrupted and that their fragments are destroyed by melting, while the basal layers are preserved intact. This is undoubtedly true, at times, but in the case of the Illecillewaet, the stratification, well seen above the cascade, has been destroyed to the very base and it is difficult to believe that the much more delicate lamination could possibly have escaped destruction at the same time. Beneath this same glacier boulders are seen fluting the under surface, as the ice is pressed against them and melted; this is shown in figures 1 and 2, plate XXXIV. If the banding were simply the original névé stratification the edges would be cut off squarely. Upon examining the ice which has been pressed against a boulder there may be seen a set of bands curving about the stone, as though they had been there produced.

Fig. 1.—Blue bands giving rise to "dirt stripes," near nose of Illecillewaet Glacier. Bands would here be conformable with strata if latter were present.

Fig. 2.—Contorted blue bands, Yoho Glacier. Supposed to indicate differential ice flowage.

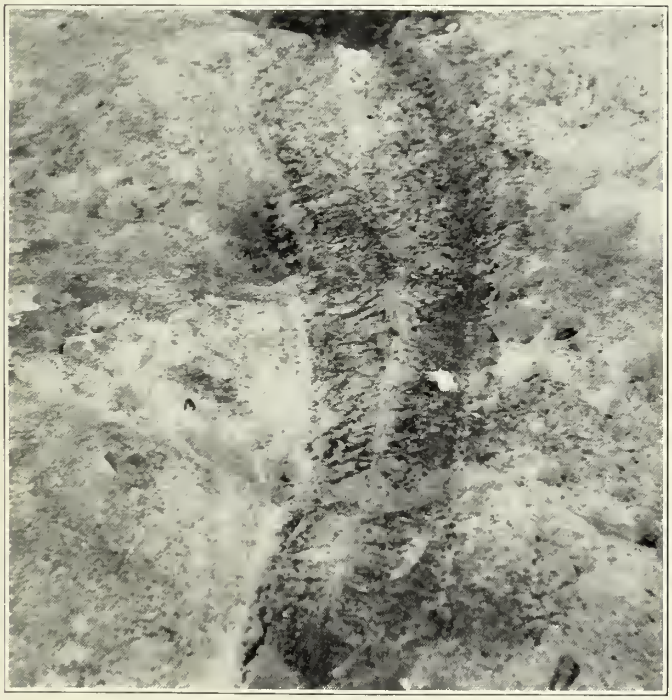


Fig. 3.—Ice dyke filled with two tiers of horizontal ice prisms meeting towards center.

Fig. 4.—Crevasse in Victoria Glacier, showing how superficial débris may attain an englacial or subglacial position.

Wherever observed, the phenomenon of blue bands suggested the structure in rocks known as *schistosity*, rather than *stratification*, the bands thinning out and overlapping. It is possible that they may still be due to pressure and yet the ice may not have become liquid, as Tyndall supposed in order to account for the scarcity of air bubbles in the blue bands, when compared with the whitish vesicular ice in which they are embedded. There may be serious doubts as to whether the pressure has been sufficient to produce liquefaction in all such cases where the bands occur, and there is no reason for thinking that the crystalline condition of the ice would be essentially different in refreezing. We may account for the irregular and often contorted banding (plate XIII, figure 2) by assuming that differential movements have occurred in the ice mass since the bands were formed. A double set might be induced without the complete obliteration of the first. It is quite possible that, in the case of a glacier of the simplest supposable type, having a very even bed and without the restraint of rocky walls or lateral moraines, the original lamination of the névé would be preserved to the nose and give rise to a certain type of "blue band." It would seem that such a type, however, could be distinguished from the more common variety and that it would lose in distinctness towards the nose. The writer had come to the conclusion that the diverse views held by investigators concerning the origin of these bands were due to the fact that two very similar structures had been studied under the same name, when his attention was attracted to the following paragraphs written by Agassiz when glacial study was still in its infancy:

"Undoubtedly, in both these instances, we have two kinds of blue bands, namely: those formed primitively in a horizontal position, indicating seams of stratification, and those which have arisen subsequently in connection with the movement of the whole mass. . . . With these facts before us, it seems to me plain that the primitive blue bands arise with the stratification of the snow in the very first formation of the glacier, while the secondary blue bands are formed subsequently, in consequence of the onward progress of the glacier and the pressure to which it is subjected. The secondary blue bands intersect the planes of stratification at every possible angle, and may therefore seem identical with the stratification in some places, while in others they cut it at right angles." *Geological Sketches*, vol. I, pp. 260 and 261.

In this report the writer uses the term *laminæ* by which to refer to these "primitive blue bands" arising in the névé, and *blue bands* for the similar, but essentially different, structure resulting, apparently, from pressure, or from some other possible agency.

g. Ice dykes. These were well developed upon the lower Lefroy in the early part of the summer, but became somewhat obscured as the season advanced. They were found sparingly upon the Wenkchemna, but were not observed upon the other glaciers studied. They consisted of gashes in the body of the ice, apparently former crevasses, from two to fifteen inches across, which were filled with columnar ice crystals. The columns varied in diameter from $\frac{1}{4}$ to 1 inch and stood at right angles to the crevasse walls, having thus an approximately

horizontal position. Very commonly the inner ends of the columns met and interlocked at the centre, but sometimes they were simply attached by their bases to the crevasse walls and left a space at the centre. Plate XIII, figure 3, will give some idea of the appearance of these dykes, although the individual ice crystals could not be made to show in a general view. As a rule the columns were straight, but sometimes curved and geniculated. The dykes were sometimes many feet in length, occasionally cutting across the walls of crevasses, presumably younger in age. In certain cases similar columns were found filling elliptical cavities in the ice, the crystals meeting at the centre. Such structures as these were observed by Agassiz upon the Aar Glacier and described by him in 1847 under the name of "*glace d'eau*." [1] Although their origin was not understood he clearly saw that they resulted from the freezing of water in cavities in the ice. The ellipsoidal cavities with their radially arranged columns were figured upon plate VI of his atlas and described under the name "*étoile de glacier*," or "*Gletscherstern*" (p. 187). These structures probably arise from the freezing of water-filled crevasses, moulins, and smaller cavities, the cooling surfaces being the walls of the cavity, instead of the atmosphere. When a lake surface freezes similar columns of ice are formed, with their main axes at right angles to the cooling surface, and, hence, ordinarily vertical. In the case of these dykes the columns also take a position at right angles to the surface of refrigeration, but these surfaces now being vertical the columns assume a horizontal position.[2] If the freezing is complete, the columns meet at the centre, the growth of the columns proceeding at about the same rate, inward from the sides. Should the water be drained off before the freezing is complete a space will be left at the centre. They are probably formed in the early part of the season, while the body of the glacier still retains some of its winter's temperature and after the melting has proceeded far enough to supply the necessary water. After being once formed they would persist through many seasons, although their upper surfaces might be obscured by various agencies. Somewhat similar dykes were sparingly observed upon the western side of the Lefroy but filled with granular ice, instead of the ice columns. Obviously these have had an entirely different history. The most plausible explanation is that they represent crevasses which were filled with the granular ice avalanched from the hanging glacier upon Mt. Lefroy.

2. Surface Features.

a. Superficial débris. The narrow valley through which flows the upper third of the Victoria Glacier, permits the avalanches of snow and ice to distribute rock débris over the entire surface. The most of this material is derived from the Mt. Victoria side, from which the avalanches may shoot completely across

[1] *Nouvelles Études et Expériences sur les Glaciers Actuels*, 1847, Première Partie, p. 185, plate VI, figures 14, 15, et 16.

[2] While this report is going through the press the author has been enabled to study the valuable paper of Crammer referred to upon page 43. Under the head of *Leisten* he describes similar structures (p. 104) and ascribes to them the origin here given.

FIG. 1.—Stony till, left lateral moraine, Victoria Glacier. Manufactured beneath hanging glacier upon Mt. Victoria and carried down with avalanches.

Whyte. Devil's Thumb. Bow Valley. Lake Louise.

FIG. 2.—Sharply crested left lateral moraine, Victoria Glacier. Moraine consists of a core of ice over which is spread a relatively thin covering of clay, sand, and rock fragments.

the valley. This being the region of accumulation, rather than melting, the rock débris is almost completely enveloped in snow and remains temporarily covered (plate v, figure 2). As the névé is pushed beyond the snow-line upon the glacier, surface melting begins and the rock fragments begin to make their appearance at the surface. As this action continues the rock rubbish is concentrated more and more, forming an almost complete veneering over the lower third of the glacier, completely obscuring the ice except where it has been incised by the drainage streams. The most of this material is sharp and angular, consisting of irregular fragments of quartzite, sandstone, limestone, dolomite, and quartz and argillaceous schists; in the main of Cambrian age. The ice lying immediately to the west of the medial moraine has come from the Lefroy side of the valley and being less well covered with débris has experienced more surface melting. This depression thus formed, shown in the cross-section along the line of plates (page 30), determined the position of the main drainage stream, previously described. The effect of this débris, in general, is to retard surface ablation and recession about the nose, so that the glacier attains a lower altitude than would otherwise be possible for it under the present climatic conditions. So far as we may judge from the ice front, the walls of the tunnels, crevasses, moulins, and drainage streams, the Victoria is not carrying much englacial material. A portion of this is in the position originally deposited in the névé and a portion has worked down from the surface by means of the crevasses, as shown in plate XIII, figure 4.

b. Lateral moraines. Along the margins of the upper Victoria and Lefroy conditions are especially favorable for the reception of rock detritus, both from the action of the ice avalanches and from the various weathering agencies that are operating upon the overtowering cliffs. Material derived from the cliff walls will ordinarily be sharp and angular, but may rarely show a single glaciated face, produced when in its original position during an earlier stage of glaciation. Most of this has been pried loose by the water in the seams and joints expanding in the process of freezing. The material carried by the hanging glaciers is almost, if not entirely, subglacial and has been subjected to severe abrading action between the ice and its rocky bed. Boulders, cobbles, and pebbles have had their corners and edges partially rounded, have had their faces bruised, gouged, and irregularly scratched, and are embedded in glacial sand and clay, of a bluish gray color. This ground-morainic material, mixed indiscriminately with that from the cliffs, is heaped up along the névé margins, embedded in snow and ice. Moved slowly along, very slowly compared with the central portions of the névé, the quantity is augmented and by the time the snow-line is reached there is formed a thick band of this débris covering the margin of the ice. Protected from the action of sun and rain more effectually than the general surface of the glacier, in spite of its débris covering, the ice beneath melts less rapidly and the marginal material is gradually elevated, with reference to the general surface. About the sides of this marginal ice ridge the débris slides and rolls down, allowing the less well protected ice above to melt into a sharp crested

ice ridge, with a veneering of rock rubbish, the whole looking like a great railroad embankment, as seen in plate XIV, figure 2. The ordinary visitor is scarcely prepared to admit the existence of the ice core, which constitutes, in reality, the main bulk of the ridge (see plate XL, figure 1, from the Asulkan Glacier). In this way are formed the lateral moraines. Should the glacier completely disappear from the valley by melting it is obvious that the lateral moraine would be gently set down along the side of the valley, forming a ridge, but of insignificant proportions compared with its apparent bulk upon the glacier.

Upon the western margin of the Victoria, the glacier's left, opposite the entrance of the tributary, there occurs a considerable mass of angular débris, contributed from the Mt. Victoria side of the valley. Most of it is arranged in three or four somewhat poorly defined ridges, parallel with the margin of the glacier. A sudden contraction occurs here in the breadth of the glacier (see plate III), and there is continued a prominent, sharp-crested ridge for one-quarter mile, marking the margin of the glacier and losing gradually in height (plate XIV, figure 2). This portion of the left lateral consists almost entirely of ground-morainic material derived from the hanging glacier upon Mt. Victoria (plate XIV, figure 1). Soaked with water after heavy rains, mud flows occur, upon the surface of which cobbles and small boulders are slowly moved down the marginal slopes, thus reducing the covering of the ice core and permitting further melting. Along the base of Mt. Whyte there are found two small moranic ridges, consisting mostly of angular material, from which the ice has withdrawn rather recently. They appear to be the continuation of the two outer ridges which farther up-stream rest upon the ice itself.

The right lateral of the lower Victoria is derived entirely from the right lateral of the double tributary, already described. It consists at first of two high, very sharply crested ridges, mainly of ground moraine, which can be traced around into the great accumulation dumped at the base of Mt. Aberdeen by the parasitic Lefroy Glacier (plate VIII, figure 1; plate XV, figure 1). The angular material has been derived mainly from Mt. Aberdeen, while the ground moraine comes from the hanging glacier of Lefroy, as previously described. The inner of the two morainic ridges is being destroyed by sliding and mud flows into the depression between it and the near-by medial moraine. In places it has become so sharp that only with the greatest difficulty can one maintain a foothold upon its crest. About 2,000 feet back from the nose, an outer third ridge makes its appearance (plate XV, figure 2), and together the three pass around and over the nose, separating into minor ridges and mingling with those of the medial and frontal moraines (plate IV, figure 1). The lower portion of this moraine has the appearance of composure and comparative stability, giving support to moss, ferns, alpine plants, shrubs, and evergreens. One Lyall's larch was noted 8 feet high and 2 inches in diameter at the base.

Since the upper Victoria receives relatively little material from Lefroy, the right lateral above the tributary is rather meagre, and inconspicuous. As

Aberdeen. Mitre. Lefroy.

FIG. 1.—Ground-morainic material manufactured beneath hanging glacier upon Mt. Lefroy and carried across Mitre Glacier by parasitic Lefroy Glacier. Beginning of ridges seen below in figure 2.

Lefroy. Victoria.

FIG. 2.—Right lateral and medial moraines of Victoria Glacier. Longitudinal ridges in lateral are well shown, the work of the parasitic Lefroy Glacier.

previously pointed out, a small amount of ground moraine escapes from being carried across the valley and moves down in the left lateral of Lefroy. In addition to this there is a large detrital cone, with its base resting upon the ice, and slowly dealing out morainic material as the ice moves down the valley (plate IV, figure 2). The covering of the general surface of the lower Victoria with rock débris prevents a great amount of differential melting, so that the lateral and medial moraines attain no great height.

c. Medial moraine. Owing to the stream-like nature of the flow, the left lateral of the Lefroy and the right lateral of the upper Victoria unite at the nose of Mt. Lefroy into a single medial moraine. This is at first a poorly defined ridge, but it becomes higher and broader as it moves across the valley from which emerges the tributary and serves as a divide for the two main drainage systems (plate IV, figure 1). Owing to the small volume of ice delivered to the Victoria by the double tributary, the medial moraine lies close to the right lateral, being separated at first by a deep depression, shown in plate XV, figure 2, which gradually disappears below as the two moraines merge. The western slope of the medial becomes long and gradual in the lower part. The entire length of the moraine is about 7,500 feet. Toward the nose it broadens as shown upon the map and in plate IV, figure 1 and becomes poorly defined, implying a sluggish condition of the ice upon which it rests. Its crevassed condition in the neighborhood of the line of plates was described upon page 37. Owing to the source of the material above noted the moraine contains a certain amount of ground-morainic material, but the bulk of it is angular and consists of quartzites, sandstone, schists, dolomite, and limestone. Some of the blocks show algæ, tracks, lingulas, and bryozoan-like stems. It has practically all been derived from Mt. Lefroy.

d. Terminal moraine. Although the front of the ice at the nose is in a condition of halt, the ice is practically stagnant and no frontal moraine has yet been formed (plate V, figure 1). Along the oblique ice front the retreat has been gradual enough to distribute the superficial and englacial rock débris somewhat uniformly over the valley floor and there has thus been formed no prominent ridge, as shown in plate VIII, figure 4. The apparent heaps seen at the right, alongside the face, still contain a core of ice, which will eventually melt and allow the rock to settle upon the valley floor. A small ridge, from 100 to 125 feet back from the ice, indicates a somewhat recent short period of halt, perhaps but one or two decades ago. It is quite probable that this halt was contemporaneous with that of the Illecillewaet, which closed in 1887. Between the oblique front and the nose conditions have been favorable for the formation of a somewhat poorly defined terminal moraine, *i. e.*, the front has been in a condition of halt while the ice was moving forward and dumping its load of angular débris. Two of the ridges that pass across the glacier, just back from the nose, extend off the ice upon the terminal moraine, without interruption, testifying still further to the sluggish condition of the ice about the nose. The medial moraine has introduced some ground-morainic material into the mass which has furnished a foothold for vegetation. Spruce and larch are climbing up the slope, the largest of the former showing

70 rings of growth and of the latter 77 rings. It is over this morainic heap that the drainage brook from the glacier cascades. The swift stream and its load of hard angular sediment have a perceptible rounding effect upon the corners, edges, and faces of even the hardest quartzites. This effect was most strikingly shown in quartzite boulders lying in the bed of a glacial stream coming from the Asulkan ridge.

c. Dirt bands. Under this term there was described by Forbes, in 1843, (*Travels through the Alps of Savoy*, p. 162), a superficial feature of certain glaciers which is of much interest and, possibly, of much importance. It is found in those glaciers which change their slope sufficiently to give rise to a distinct system of transverse crevasses, not necessarily to a cascade or ice-fall. The phenomenon was not understood by Forbes himself and, by various writers since,[1] has been confused with the *dirt zones*, described upon page 39, which are the outcropping edges of variously marked strata. It is to the keen observation and shrewd interpretation of Tyndall that we are indebted for the true explanation[2] of the feature. The Victoria and the Lefroy glaciers furnish an excellent opportunity for the study of dirt bands under very simple conditions, as well as the dirt zones for comparison. The two types of structure may be gotten upon the same photographic plate and are well shown in plate IV, figure 2. In very simple form the dirt bands may be seen cutting across the dirt zones upon the lower Lefroy, owing to the abnormal position of the latter. Under ordinary conditions the two would be more or less conformable and possibly difficult to separate.

The typical dirt bands are of such a nature that they can be seen most strikingly at a distance of a half-mile or more from the glacier and at a considerable elevation above it. When once seen, however, it is possible to locate them in a very general way while upon the surface of the glacier itself. In the summer of 1904, from the summit of the Devil's Thumb, which overlooks the Victoria Glacier from a height of 8,000 feet, there could be counted 23 soiled streaks passing across the glacier. Beginning near the crest of the ice slope opposite the nose of Mt. Lefroy, the bands were narrow, straight, and extended nearly across the glacier. They showed so dimly that there was uncertainty in regard to the count, until they had been gone over a number of times. Upon the face of the slope they became more distinct, curved so as to be convex down-stream, and correspondingly shortened. A few of them could be traced around into the transverse crevasses which had not been completely closed. Beyond the foot of the ice slope the bands became still better defined, especially upon the *southern*, or up-stream margin, narrower, more closely placed, and changed their shape from arcs of circumferences to hyperbolas. Towards the lower end of the series the bands became much shorter, the arms extending into and blending with the surface débris, and their apices appeared to mark the locus of maximum surface velocity

[1] Agassiz, *Geological Sketches*, vol. I, pp. 244 and 254; Russell, *Glaciers of North America*, p. 43; Hess, *Die Gletscher*, p. 169.

[2] *Glaciers of the Alps*, pt. II, chapter 26.

FIG. 1.—Formation of Forbes's "dirt bands," Deville Glacier, Selkirks. From summit of Mt. Fox (10,572 feet), looking eastward. Photographed, 1902, by Arthur O. Wheeler.

FIG. 2.—Forbes's "dirt bands," Victoria Glacier. Photographed from the Lefroy Glacier, July, 1904. Often confused with "dirt zones." Compare figure 2, plate XI.

of the ice. Finally the bands mingled with the superficial rock covering of the glacier and were lost. Standing upon an individual band the dark color seems to be imparted by the fine dust and sand and not by the coarser débris. In September, 1905, owing to the excessive melting of the summer, the bands stood out with unusual clearness, so that they were photographed from the side of the Lefroy Glacier, as shown in plate XVI, figure 2. By signaling to an assistant, the well defined up-stream margins of 19 of the bands were located by erecting small cairns of rock, and their distances apart, in the line of their apices, were later measured (see map, plate III). The results were as follows, beginning near the foot of the ice slope. The average interval between the bands is 97 feet.

Band	Interval	Band	Interval
Band No. 1		Band No. 10	
	159 feet		100 feet
" No. 2		" No. 11	
	174 feet		86 feet
" No. 3		" No. 12	
	126 feet		88 feet
" No. 4		" No. 13	
	124 feet		57 feet
" No. 5		" No. 14	
	113 feet		81 feet
" No. 6		" No. 15	
	109 feet		66 feet
" No. 7		" No. 16	
	100 feet		83 feet
" No. 8		" No. 17	
	83 feet		83 feet
" No. 9		" No. 18	
	75 feet		45 feet
" No 10		" No. 19	

For reasons to be given later the writer believes that the intervals between these bands mark the annual progress of the ice down the slope, as conjectured by Tyndall, and offers the following explanation of the phenomenon. As the ice of the glacier is pushed over the crest of the ridge in its bed, which is responsible for its change in surface slope, there is formed successively a series of transverse crevasses, as explained upon page 36 of this report. The distance between these crevasses will be determined mainly by the thickness of the ice and the change in its angle of slope. Since the glacier is moving forward in winter as well as summer, although at a less rate, these crevasses must originate at all seasons of the year. Those which have been formed in the late fall, or winter, upon passing down the slope will be perfectly healed, since their lips have experienced practically no melting from the sun's action. The opposite crevasse walls come slowly together, refreeze, and leave no visible scar in the ice. Those crevasses, however, which have formed in the late spring and summer have their lips much rounded by the sun's rays. If the glacier is moving northward as in the case of the Victoria and Lefroy, the northern, or down-stream lip of the crevasse will receive the maximum effect, the southern comparatively little. Should the glacier be moving southward, the northern lip of the crevasse would still be the one most strongly acted upon by the sun, but in this case it would be the up-stream side. Glaciers flowing east or west, and having their transverse crevasses in an approximately north-south position, would have their crevasse

walls affected more evenly, unless surrounding mountain cliffs interfered. In the healing of such crevasses there would be left a depression, representing the sun's action upon the lips of the crevasse, not simply for one season but through a series, and in this depression the wind-blown dust would collect and the fine débris would be washed by rain and melting ice from the adjacent portions of the glacier, rendering it lighter by contrast. Owing to the more rapid central movement of the ice the bands, at first nearly straight, will begin to curve downstream and become more and more sharply bent, their apices marking the locus of maximum surface motion. Between them will lie swellings, or ridges, having the same general form of the depressions, from which much of the finer dirt has been removed. These ridges and intervening depressions may be very inconspicuous, as upon the Victoria, or they may become very prominent, as shown upon the Deville Glacier in the Selkirks, forming what Forbes termed "wrinkles" (plate XVI, figure 1). They mark that portion of the ice which passed the crest of the slope in the late fall and winter and appear as ridges, partly because of the severe compression to which the ice is subjected and mainly because the adjacent ice has been lowered by melting. Owing to the more rapid movement of the ice down the slope the bands will be farther apart and less well defined, than after the more gentle slope below has been reached and the ice is subjected to longitudinal compression. Upon this more gentle slope they have a better chance to catch and retain the fine débris. Since the sun's action was more powerful at the center of the crevasse, the depression is greater at the apex of the band and persists after that of the extremities has been finally lost by surface melting. In consequence the bands become shorter and shorter and lastly disappear, when ablation has reduced the surface to a general slope and the fine débris is redistributed. Very often it must happen that instead of a single crevasse being formed during the season of melting there would be formed a series of them. Upon a steep slope of the Asulkan they seem to be formed in pairs as shown in plate XVII, figure 1, in which it is seen that the ridge of ice separating two adjacent crevasses is acted upon from either side and lowered, assisting in the formation of the depression. The crevasses that are forming the depressions, preparatory to the reception of the dirt, may be traced around to the almost healed crevasses at the left, while between them are seen traces of crevasses that have healed with practically no marginal melting. These are presumably those which opened and closed soon enough to escape the rounding action. If the surface slope is too great the depression produced in the ice may not be sufficient to retain enough dust to bring out the series distinctly, as is the case with the Asulkan just noted. Study figure 1, plate XXIX, from the Yoho Glacier.

That the method of formation of these dirt bands is essentially as outlined above admits of no doubt. The question as to whether they are produced annually, or at irregular intervals, needs to be investigated. The average interval of those bands originally described by Forbes upon the Mer-de-Glace was 711 feet. Opposite his station D the interval was 667 feet (*Travels through the Alps of Savoy*, p. 165). In a postscript to his volume, p. 420, he gives the move-

FIG. 1.—Formation of Forbes's "dirt bands," steep portion of Asulkan Glacier. August, 1904.

FIG. 2.—Dust wells, Victoria Glacier, the result of differential melting. In small quantities dirt facilitates melting.

FIG. 3.—Small dirt cone, Victoria Glacier. In sufficient quantity the rocky débris retards surface melting.

FIG. 4.—Same cone shown in figure 3, with dirt veneering removed from one side to show ice core.

ment of one of the lateral points opposite station D as 483 feet for the year and suggests that "the movement of the center is probably, at least, two-fifths greater, corresponding closely with the intervals of the 'dirt bands' of the glacier." Although the size of the intervals in this series differs plainly to the eye, still Forbes states that the difference for any one interval is probably not a tenth of the mean. From the same point of view as that used by Forbes in 1842, Tyndall counted upon the Mer-de-Glace, 17 years later, exactly the same number of bands and remarked: "The entire series of bands which I observed with the exception of one or two, must have been the *successors* of those observed by Professor Forbes; and my finding the same number after an interval of so many years proves that the bands must be due to some regularly recurrent cause." In Chapter XXXII of his *Glaciers of the Alps*, Tyndall has described his "white ice-seams," the "bandes lactées" of the French and "weissen Blätter" of the Germans. These are due, in part, to the filling of transverse crevasses, left open during the fall, with snow and then its later compression into a white vesicular ice. Since, in general, these crevasses would be those which had been acted upon by the summer sun, they would be the counterpart of the dirt bands under discussion. Sèvé found the average interval for these white seams upon the Böium Glacier, in Norway, to be 218 feet and that this represented also the average forward annual movement.[1] So far as the Victoria Glacier is concerned we have not sufficient data at hand to settle the question of the annual character of the dirt bands. At the line of plates, about a third of a mile below, the maximum annual movement of the ice was found to be 65.85 feet. The average annual interval for the lower half of the series is 76.56 feet, which is about what would be expected in the way of annual ice movement, when compared with the above. We should also expect the movement to increase as we approached the crest of the ice slope. So that the actual and relative spacing of the bands very strongly suggests their annual character. If due to some "regularly recurrent cause," as Tyndall suggests, this cause must recur with the seasons.

We are, however, not entirely without evidence that the intervals between the dirt bands indicate approximately the annual movement of the ice. As pointed out upon page 30, the Messrs. Vaux marked the location of a large boulder upon this portion of the glacier July 26, 1899. From range lines, one year later, they determined that the boulder had moved forward 147 feet. In September, 1905, this boulder was found opposite the 9th band of the series given upon page 51. In 1899 it should have lain opposite the 3rd band and, if the motion there had been the same as it was in 1904–5, it should have moved in 1899–1900 the distance of 126 feet. The previous year it should have moved 174 feet. My field notes say that the second and third bands were indistinct, so that there is strong probability that the three intervals between one and four may not have been properly distributed. The average for the three is 153 feet, which agrees very well with the actual observed motion of the boulder. If the dirt band intervals are an approximate indication of the annual ice movement

[1] Quoted from Heim's *Gletscherkunde*, p. 140.

the Vaux boulder had moved downward in 1905 from its original position some 676 feet, or at an average rate of about 113 feet per annum.

f. Dirt stripes. Somewhat closely related to the dirt bands just described, so far as their method of formation is concerned, are the fine streaks of dirt seen along the margins of most glaciers, sufficiently free from surface débris. They may be found, however, anywhere upon the glacier that the blue bands are well developed, reach the surface at a fairly steep angle and are being subjected to surface melting. The blue bands, being composed of relatively firm, compact ice, are more resistant of the sun's action, than the vesicular ice in which they are embedded and project as delicate ridges, separated by narrow furrows. Into these furrows the wind-blown dust settles and is washed from the adjoining ridges, forming narrow, parallel dirt streaks, or stripes. When well developed, as upon the Lefroy, the glacier has the appearance of having been swept with a coarse wire broom; the strokes having all been long, regular and parallel. The dirt stripes mark the position of the vesicular bands in the ice and the lighter streaks between the position of the blue bands themselves. In this way the banding is clearly shown at the surface, whereas, otherwise, it might be obscure. Views of these stripes have already been shown in plate XII, figure 4 and plate XIII, figures 1, 2. Sometimes they run down the face of a crevasse wall (plate XII, figure 4), as though they might be something more than a superficial feature, but a little chipping of the ice shows plainly that they are not. After they have once been formed the dirt stripes will absorb the sun's heat and still further emphasize the small furrows. Running, in general, lengthwise of the glacier these furrows become the sites of minute rills which have a tendency to clear away the fine dirt, as fast is it collects. For this reason, as well as because of the nature of the banding itself, the individual stripes are not continuous for any considerable distance. They are sometimes so closely placed that 10 stripes may be counted within the distance of an inch, but are usually considerably coarser.

g. Dust and pebble wells. Where small pebbles, or patches of fine dirt, often black from the presence of organic matter,[1] are thinly distributed over the surface of the ice, heat is absorbed and the ice immediately beneath is melted more rapidly than the surrounding ice. Cavities are thus formed with vertical walls, which for a time retain the water. They sink into the ice for a few inches, until protected from the direct rays of the sun by their own walls, when further melting would be delayed until the general surface was lowered sufficiently to allow the sun to again reach the foreign matter at the bottom. Such wells are shown in plate XVII, figure 2. Although their depth at any one time is seldom greater than a finger's length, still in the course of the season their total length would be 9 to 10 feet upon the Victoria and Lefroy. A thin film of water often freezes at night over the surface and then thaws out promptly when again exposed to the sun. After thus freezing the water is at times drawn into the

[1]A sample collected from the Illecillewaet in 1903 contained 14 per cent. of organic matter, enough so that when set away moist in a warm room it soon became offensive.

glacier, by means of the capillaries developed between the granules, leaving the well free from water, but with its ice cover. Where pebbles, or small dirt patches, are abundant, as shown in the last figure, the ice between the adjoining wells is melted more rapidly by the sun than it would ordinarily be, forms minute pinnacles and appears whitish and spongy. In this way the lowering of the general surface of the glacier by ablation is accelerated. By keeping itself thus at the bottom of a small well the dirt of these small patches is prevented from being blown away, or washed away, and thus it is possible that the same well may persist through, not only a season, but a succession of seasons. Should the well, however, collect additional dirt, beyond a certain limit, this excess would then *protect* the bottom of the well from further melting, the adjoining ice would soon be lowered below the bottom of the well and the well would be literally turned *wrong-side-out*. Where one has a few days to spare about the same glacier an interesting experiment would be to sift dirt into a group of typical wells, filling them to varying depths, and observing the result. Such an experiment may easily be performed upon a snow bank of sufficient depth, when it is being strongly acted upon by the spring sun. It would prepare the way for a clear understanding of the next three surface features to be described.

h. Débris cones. When the amount of dirt, sand, gravel, or rock débris, is sufficient to protect the surface of the ice from melting, or to even partially protect it, over a limited area, the surrounding ice surface will be lowered more rapidly than that beneath the protecting material and the débris will begin to be elevated, with reference to the neighboring surface. The loose débris will slide, or roll down about the side, exposing the edges and corners to the melting action of the sun, allowing still more sliding of the débris and still further melting. The ice core will finally assume the form of a ridge, cone, or mound, with its thin veneering of foreign matter, as in the case of the lateral and medial moraines already described. The companion figures 3 and 4, plate XVII, show the structure of a small gravel cone, only 15 to 16 inches in height; figure 3, as it was found upon the ice, figure 4, after the gravel upon one side had been washed off to show the ice core. It is seen what a thin covering will suffice to bring about the result. Depending upon the nature of the covering they are known as dirt, sand and gravel cones, and boulder mounds, and they may vary in height from a few inches to many feet. In plate XIX, figure 1 is shown a mound upon the Wenkchemna Glacier, estimated to be 80 feet high. This pile of rock rubbish was either dumped in a heap by an avalanche, or collected in the bottom of a lakelet, as described by Russell for the Malaspina in Alaska.[1] Cones of all types, varying in height, from a few inches to 12 or 15 feet are to be found upon the Victoria in the region of maximum melting. They may persist from one season to another, but there is a limit to the height to which any particular cone may attain. As the height of the cone grows the lateral surface is increased, over which the débris must be spread in order to suffi-

[1] *Glaciers of North America*, p. 115.

ciently protect the ice. When this covering becomes too thin, or when it is blown off, or washed down the steep slopes by heavy rains, the ice core becomes exposed and rapid melting ensues, resulting in the destruction of the feature. In case the surface covering is distributed about the base and the pure ice core exposed, the melting does not cease when the general level is reached but continues more rapidly than the surrounding ice to which has been transferred the débris. Instead of a cone, we may now get a basin-shaped depression, which is gradually extended laterally by melting, and into this depression the original material may again slide and be collected at the centre until there is sufficient to prevent further melting. An interesting and instructive experiment, in connection with that suggested upon the dirt wells, is to wash down the gravel, sand or dirt, from a collection of small cones, mark the location, and watch the changes from day to day.

i. Glacial tables. In the case of a single rock fragment, of sufficient size, resting upon the ice over which surface melting occurs, protection is afforded the ice immediately beneath. As the result of the more rapid melting of the surrounding ice the rock is relatively elevated upon a pedestal of ice and there results what is termed a "glacial table"; as seen in plate XVIII, figure 1. As the rock is elevated a short and narrow ridge of ice lying to the north of the pedestal (observe the shadow in the figure) is protected from the noonday sun, so that viewed from the east or west the pedestal is unsymmetrical. This lack of symmetry is further emphasized by the undercutting action of the rays of the noonday sun upon the southern side. Some observations were made with a view of discovering the lower limit of the rock fragments that were capable of furnishing the protection necessary to form tables. The following were found forming low tables, or starting to form them. It is obvious that the color and nature of the rock would both have their influence in determining the effect upon the ice.

Dark gray limestone,	12 x 12 x 4.5 inches.
" " "	13 x 9 x 3 "
Light " "	11 x 6 x 3.5 "
Reddish quartzite,	10 x 8 x 2.5 "
Rusted limestone,	9 x 4.5 x 1 "
Dark limestone,	8 x 4 x 2.5 to 3 inches.

In the case of the last specimen the thicker end was found to be protecting, while the thinner was inducing melting. Owing to the undercutting action of the sun's rays blocks of this size can form only low tables. Larger blocks may rise to a height of three to five or six feet upon the Victoria, the latter heights being unusual. They may persist from one season to another but there is a limit to the height which any particular table may attain, determined mainly by the size and shape of the rock. As the rays undercut, mainly upon the southern side, the block begins to lean to the south and finally topples off in that direction (plate XVIII, figure 2). The remnant of the pedestal is removed by

FIG. 1.—Glacial table, Victoria Glacier, looking southwest. Observe undercutting action of rays upon south side and shadow cast by the rock upon north side, with resultant ridge of ice.

FIG. 2.—Dethroned glacial table, Victoria Glacier, looking northeast. The boulder fallen to the south by undercutting action of sun's rays.

FIG. 1.—Boulder mound, Wenkchemna Glacier, illustrating the protective effect of rocky débris. Estimated to be eighty feet in height.

Whyte. Devil's Thumb. Bow Valley. Fairview.

FIG. 2.—Surface lakelet, Victoria Glacier, resulting from lack of débris protection. Enlargement towards right is still in progress by melting, but has practically ceased towards the left, owing to the rocky cover.

melting, the block settles into its position of equilibrium and the making of a glacial table begins anew. In exceptional cases the undercutting of the pedestal may be done by a surface stream. In the case of 25 tables selected at random, it was found that the longer of the horizontal axes of the pedestals had an average magnetic bearing of N. 36° W., or 11° W. of true north. With a larger, or a different, series, the average would probably be more nearly the true north.

j. Surface lakelets. Upon the middle portion of the Victoria, western side, where the ice is presumably quite stagnant, there occurs a series of surface lakelets, the crater-like basins of which have been hollowed in the ice. The largest of this series is somewhat elliptical in form, 200 feet long by 100 feet broad (plate XIX, figure 2), and filled with deep blue water in which miniature ice-bergs may be seen floating about. The southern and eastern banks of the lakelet are from 12 to 20 feet high and under cut, apparently by the melting action of the lake water. The northern and western banks have been acted upon more strongly by the sun, causing them to recede and the débris to slide down until the margins of the lake are filled and the ice banks veneered sufficiently to retard melting (plate XIX, figure 2). These banks are as steep as the débris can stand and from 25 to 30 feet in height. From the still steeper ice walls the gravel and small boulders are splashing into the water with a sound suggestive of considerable depth. The lake has no visible outlet and persists from season to season. Several similar lakelets, but smaller, occur in the same vicinity, some having their sides completely veneered with rock débris, which has checked melting and allowed the lakelet to become almost dry.

These lakelets may have originated in marginal crevasses and been enlarged and shaped by melting, or they may have originated by surface melting over certain limited areas less well protected by débris covering. In the preceding discussion of débris cones it was shown how miniature basins might originate. In a stagnant portion of the glacier it is possible that the basins of such lakelets might arise in a similar manner from such a mound as that figured from the Wenkchemna Glacier (plate XIX, figure 1). The rock débris rolling or sliding to the base would leave the cone sufficiently bare to permit rapid melting to a depth at which the marginal débris would begin to slide back again. The accumulation of the débris in the basin would check further melting at the center, while the surrounding ice has lost, in proportion, a part of its débris. As observed by Russell upon the Malaspina, the surrounding ice would be lowered until the basin disappeared and what had been the centre of the basin would become the crest of a boulder mound. If conditions remained favorable, *i.e.*, sufficient thickness of stagnant ice and continuous surface ablation, the sides of the mound would become more and more steep, as it gained in height and the time would come when the bulk of the débris would slide or roll to the base, the ice core would be removed to the general level and a new basin would be started. For the larger lakelets the complete cycle would probably have to be reckoned in decades and centuries.

k. Rock reflection (?). A final surface feature remains to be described, al-

though a satisfactory explanation has not been found. Observations were begun upon the Victoria in 1904 before the winter snow had disappeared from the lower half of the glacier, which is ordinarily bare in the summer. It was noted that as the surface boulders protruded through the snow a larger percentage of them showed melted areas upon their *northern* sides, the shape and size of which sustained a certain relation to the breadth, height, shape, and possibly position of the boulders themselves. Over the melted area the snow was removed, in whole or part, to the soiled surface of the glacier, so that the feature shows with much clearness in the photographs secured. The phenomenon was seen upon the Lefroy, as well as the Victoria, and sparingly upon the Wenkchemna in midsummer, near the névé lines. The same thing was also seen upon the snow of an avalanche which had descended from Mt. Whyte and carried along some small rock fragments, which were scattered over the surface. The block shown in plate XXIV, figure 4 is a gray quartzite standing 10 inches high and is 29 inches broad. The melted area has the same length as the rock and has a correspondence in outline. The farther right hand corner of the rock is somewhat lower than the general surface and the corresponding corner of the melted area is seen to be rounded and incompletely melted. Boulders showing the phenomenon were not hard to find upon the Victoria, but were very abundant. The north-south axes of ten of the areas, selected at random, gave an average magnetic reading of N. 25.5° W., with less range than was shown in the case of the glacial tables. The magnetic declination of the region, as obtained by the Canadian Topographic Survey, is N. 25°5′ E., so that these areas are oriented with reference to the noonday sun, and might have been used for determining approximately the meridian and the magnetic declination. The natural inference is that the phenomenon is due to the reflection of heat from the surface of the boulders, this action being at a maximum when the sun is upon the meridian.

3. Former Activity.

a. Terminal moraines. Between the present poorly defined terminal moraine, described upon page 49, and Lake Louise there occurs a series of ancient terminal moraines which furnish evidence of the glacier's former extent and greater activity. The first two of these moraines are remarkable in that they consist of massive blocks of quartzite and sandrock, tumultuously heaped together and without the usual filling of gravel, sand, and clay. The position of these is shown upon the map, plate III. The spaces between the great blocks enable man, or animals, to creep in between and under them and they form an ideal home for the marmots. For moraines of a somewhat similar appearance, although probably different history, in the Mount Ktaadn region Prof. R. S. Tarr has used the expressive term "bear-den moraine."[1] The inner of these two moraines extends obliquely across the valley from the present nose, being partially overridden by the glacier and along the side of the valley nearly parallel with the oblique front. It consists of what were originally massive

[1] Glaciation of Mount Ktaadn, Maine. *Bulletin Geol. Soc. of Amer.*, vol. XI, 1900, plate 37.

blocks of quartzite, sandstone, and schist tumultuously heaped into a ridge 30 to 40 feet high. The sandstone and schist have undergone considerable disintegration, in place, forming more or less soil which supports a growth of moss, shrubs, spruce, and fir. The rings of growth, in the spruce and fir of the Lake Louise Valley, were found to average 0.884 mm., and, in the case of the averages for individual trees, to range from 0.51 mm. to 1.26 mm. As the tree matures the new rings are excessively thin; owing to the reduction in the relative amount of leaf surface, the scant precipitation, the short growing season, and the lack of direct sun light in a deep valley with a north-south trend. The largest tree found upon this moraine gave a circumference of 221 cm., at a distance of 50 cm. from the base, and should be approximately 400 years old. The material of this moraine is arranged in two main heaps, between which the glacial brook passes, that upon the eastern side having come from Mt. Lefroy and that upon the west from Victoria. After the formation of the moraine the glacier retreated up the valley to a point greater than that occupied by the present nose.

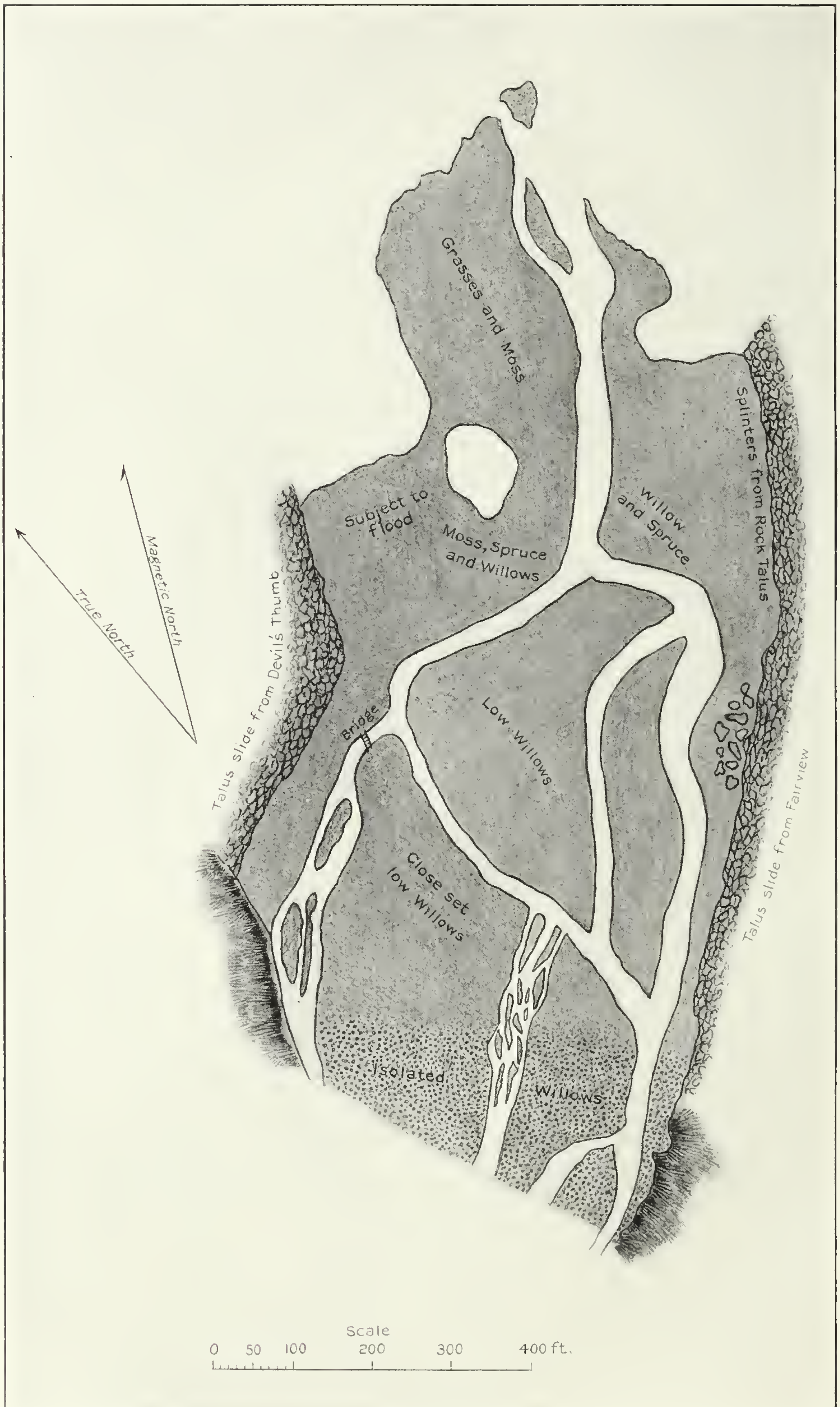
From 300 to 800 feet farther down the valley there occurs the second of this type of moraines, the blocks consisting very largely of quartzite, lichen-covered and moss-grown, but not disintegrated. As in the case of the preceding moraine the blocks are disposed in two heaps, upon either side of the glacial brook, the bulk of it lying to the west, where it forms an oblique ridge 700 to 800 feet long, with a maximum breadth of 300 feet and a height of 70 to 80 feet. Made up of such coarse blocks and with no filling of sand, gravel, or clay the whole presents a very imposing mass and impresses one with the possible importance of glaciers as geological agents. The largest block seen had split in falling, measured 31 x 25 x 15 feet, and was estimated to weigh 970 tons. The blocks are generally sharp and angular and have not been subjected to stream or ice action. They were carried either upon the ice or within it and show almost no signs of ice abrasion. An occasional single face is glaciated but in such a way as to show that this was done when, in its original position, it formed the face of the cliff. Owing to the lack of soil the growth of shrubs and trees is scant. The largest spruce seen upon the moraine itself was estimated to be 450 years old, while another just beyond the outer edge was estimated at 580 years. Upon the side of Mt. Whyte just at the line of plates, there is a large collection of similar blocks, and apparently of equal age, which appear to have become stranded here while the others were undergoing transportation. It should be noted that the present Victoria is entirely incapable of making such a moraine now, no matter how prolonged the halt. The present terminal moraine, and the oldest of the series to be described, are essentially alike but very different from these great block, or bear-den moraines. The cliffs which contributed the bulk of the material, so far as we may judge from their favorable situation and the location of the blocks, have a north-northwest trend and the blocks fell from them to the eastward.

Down the valley, a distance of one-quarter of a mile, there occurs a double detrital cone, derived from the opposite mountain slopes of Mt. Whyte and Castle

Crags. The slide from the latter slope is still in process of formation and consists of freshly broken angular fragments. That from Mt. Whyte is older and covered with spruce, fir, and willow. This material overlies, and almost conceals, a triple moraine, composed of boulders, gravel, and clay. The inner and higher ridge of the three curves regularly across the valley and in one place about 60 feet of it have been cut away by the drainage brook. It here has a breadth of 100 feet, a height of about 20 feet, and consists largely of a yellowish, stony till. Between it and the outer bear-den moraine the drainage stream has filled in with sand and gravel, forming a nearly level flat. Lower down the slope and 400 feet distant, there is another morainic ridge, approximately parallel with the first, but made up more largely of boulders while 350 feet farther on there is a third ridge containing a higher percentage of yellowish clay.

b. Lake Louise basin. This lake is roughly elliptical, with a major axis of $1\frac{1}{4}$ miles and a width of $\frac{1}{4}$ to $\frac{3}{8}$ of a mile, placed with its longer axis parallel with the valley (see plate I and plate XIV, figure 2). The chief irregularity in the outline is due to the presence of a rock slide from Mt. Fairview and to the delta deposits at the head. The level of the lake is given by the Topographic Survey as 5,670 feet above sea level. This level, however, fluctuates in the course of the season and from year to year, being some 15 inches higher in the spring, as a result of the rapid melting of the snow. Four determinations upon the inflow at the head gave an average of 80 cubic feet per second. Two measurements upon the outflow, through a rectangular orifice at the dam, gave an average of 88 cubic feet per second, the lake receiving a small additional flow from Mirror Lake and Lake Agnes. In midsummer, owing to the presence of the glacial sediment, the lake has a superb green color, but during the winter this has a chance to settle to the bottom and in the spring the color is more of a blue, the natural color of pure water.

From the studies of Mr. W. D. Wilcox, reported in the paper previously cited (page 7), the basin of the lake is seen to be a U-shaped trough, with a maximum depth of 230 feet just beyond the centre. This shows that the valley was excavated by ice and that, in all probability, the bottom of the lake is a glacially excavated rock-basin, similar to that of Lake Agnes, just west but at a higher level. Bedrock is found upon all sides of the lake, except about the foot, where there is the ground-morainic dam previously described (page 8), filling the valley to an unknown depth. At the head of the lake the valley walls are much contracted, being but 570 feet apart. They consist of a very firm quartzite, in the main, with a little slaty schist, dipping up the valley at an angle of 10° to 15°. This feature of the valley must have greatly contracted the ancient glacier passing through the gateway, caused it to thicken correspondingly and to vigorously gouge out its bed until it had a chance to again expand laterally. In this way we may account for the presence of the rock-basin, but should expect the deepest part of it to be somewhat nearer the head of the lake than is shown in Wilcox's contour map. It is not at all improbable, however, that the deepest part of the rock-basin is really so located and that there has been a



Map of delta, head of Lake Louise, by W. H. Sherzer. Plane-table survey, July, 1904. Field assistants De Forrest Ross and Frederick Larmour.

filling of the lake bed here with glacial sediment and débris from the Mt. Fairview slide, to the extent, at least, of 50 to 60 feet.

c. Lake Louise delta. After the ancient Victoria permanently retreated from the head of the lake, there began the formation, at the head of Lake Louise, of a gravel, sand, and silt delta, which is a minimum measure of the amount of glacial erosion that has since been taking place in the upper part of the valley. This delta extends into the lake 400 feet, with an average breadth of about 300 feet, as shown upon the map, plate XX, that was prepared with a plane-table in July, 1904. A shelf of fine sediment borders that portion above water and then drops off rapidly, forming a layer of unknown thickness over the bottom of the lake. Much of the delta is elevated but 10 to 12 inches above the lake level and is under water during high water stages of the lake. Portions of it are flooded during midsummer after periods of excessive melting. In this way the delta is gradually growing in height. Low, broad levees line the main stream. This comparatively small portion, which projects into the lake, is simply part of a very much more extensive deposit of glacial silt, sand, and gravel, which reaches up the valley for a distance of $\frac{1}{4}$ to $\frac{1}{3}$ of a mile and has a breadth of 500 to 600 feet. Over this very gradual slope the glacial drainage courses in three rapid, turbid streams, which unite into a single channel, 40 to 50 feet broad and one to two feet deep. Grasses and moss cover the lower, flat portion of the deposit, close set willow and spruce the central part, and isolated willows the upper gravelly region. The rock-slide from Mt. Fairview has encroached upon the lake as well as the morainic dam at the foot of the lake, upon which stands the chalet. Between this dam and the range of mountains in the background lies the Bow River Valley, which supported a great trunk glacier, leading eastward from the mountains (plate XIV, figure 2).

d. Lake Louise Valley. When the mountains were in process of making it is very probable that this valley began as a structural feature either as a trough between mountain folds, or from the opening of a joint in the rock strata. Before the coming of the glaciers it is probable that ages of stream action, aided by atmospheric weathering, deepened and broadened the original feature into a V-shaped valley. With the advent of the perennial snowfields a new geological agent entered, deepening the bed and broadening out the base so that the cross-section of the valley, particularly the lower half, assumed the characteristic U-shape of glacially excavated, or glacially modified valleys. An inspection of the general views of the valley, such as plate I, shows a lower portion with steeply inclined, nearly vertical walls, while the upper portion has more flaring walls, the arms of a truncated V. This upper portion was glaciated to a height of about 9,000 feet above sea level, or some 3,000 feet above the valley floor, the walls being smoothed and fluted and the spurs evenly truncated; see the shoulder of Mt. Fairview at the right in plate XIX, figure 2. It is not improbable that these more gentle, higher slopes represent portions of the original pre-glacial valley, produced mainly by the action of weather and running water, and not very materially modified by the ice. These slopes produced until they intersect may

be assumed to represent approximately the original valley before the ice invasion. The lower portion, with the very steep walls and broad base, probably represents that portion of the valley which was profoundly affected by the great ice stream that so nearly filled the valley. The destruction of the strata necessary to secure such a result was very probably accomplished by the disrupting power of the ice, known as "plucking."

e. Ancient till sheet. The rock débris was, in great part, delivered to the Bow Glacier and carried beyond the mountains. The finer portions, consisting of gravel, sand, and clay, with some cobbles and boulders, secured lodgment in certain favorable places, particularly near the mouth of the valley, and compacted by the great weight of ice formed the ground moraine, or sheet of till. From 75 feet to 100 feet of this deposit have been exposed between the foot of the lake and the Bow River, but the maximum thickness was very probably much greater. It forms an irregular sheet, of unknown extent and thickness, reaching up to and under the modern glacier, mantling the actual rock bottom of the valley. It is entirely without stratification and the rock fragments are largely bruised and scratched. The color, as seen in the exposed sections, is a brownish-yellow, as the iron of the clay is being slowly oxydized. The more deeply buried beds would, undoubtedly, show more of the bluish-gray, which characterizes this material when it is fresh.

CHAPTER IV.

WENKCHEMNA GLACIER.

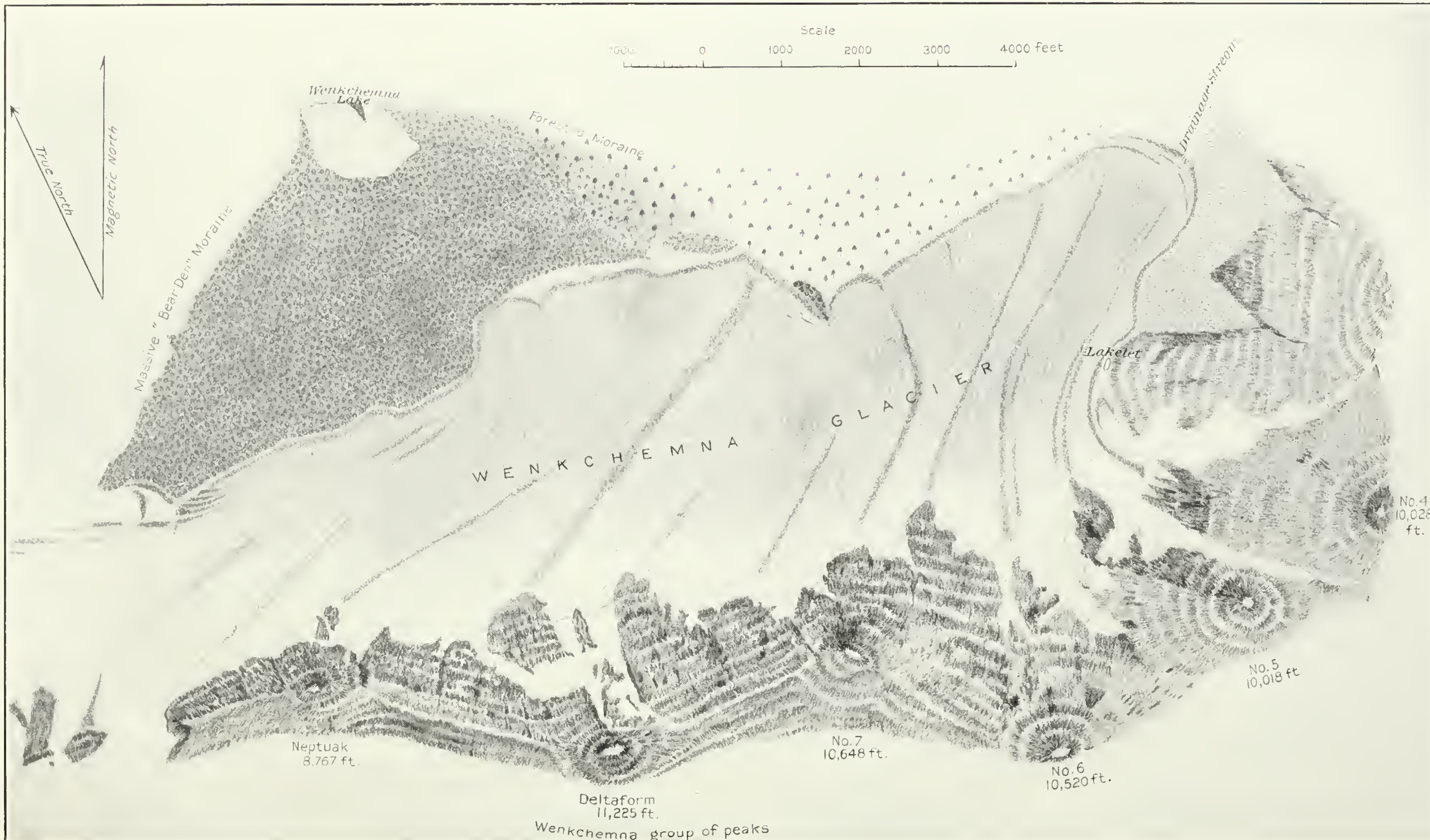
1. General Characteristics.

Nestling close in behind the northern base of that grand array of peaks for which the Canadian Geographic Board has recently adopted the name Wenkchemna Group lies the Wenkchemna Glacier. The name is of Sioux origin, *wikchemna* signifying ten, and was given the glacier by Mr. S. E. S. Allen, in allusion to its relation to the series of ten peaks upon which he bestowed the Indian numerals. These peaks, the highest of which has been rechristened Mt. Deltaform, with their high connecting ridges constitute here the great Continental Divide (plate XXI). Between them and Mt. Temple lies a broad valley originally called "Desolation Valley" by Wilcox, but now known as the Valley of the Ten Peaks. The glacier occupies the southern half of the upper third of this valley, and faces north, while the valley itself slopes eastward and then northeastward. In a direct line it lies only about six miles south-southeast from the Victoria, and may be reached by crossing the Mitre Pass, encircling the Horseshoe Glacier at the head of Paradise Valley and entering the Valley of the Ten Peaks by the Wastach Pass. The ordinary way of reaching the glacier, however, is from the chalet at the foot of Lake Louise, over a good trail to Moraine Lake, where a summer camp is maintained by the Canadian Pacific Railway. From

Fay. No. 2. No. 3. No. 4. No. 5. No. 6. No. 7. Deltaform. Neptuak.

Moraine Lake. Drainage Stream. Wenkchemna Glacier.

The Continental Divide, Canadian Rockies, Valley of the Ten Peaks. Photographed in 1903, from summit of Mt. Temple (11,626 feet), by Arthur O. Wheeler, Canadian Topographical Survey.



Map of Wenkchemna Glacier, Valley of Ten Peaks, Canadian Rockies. Surveyed and drawn by W. H. Sherzer, August, 1904. Field assistants De Forrest Ross and Frederick Larmour. Adjacent region based upon maps of A. O. Wheeler and D. W. Wilcox.

this camp, at the foot of the lake, the trail is rough for horses, but practicable to the front of the glacier, about two miles distant.

Quite in contrast with the Victoria, and with mountain glaciers in general, the Wenkchemna presents noteworthy peculiarities of form, in that it is very broad for its length and has a remarkable amount of frontage. Its breadth is about three miles, while its length is from one-half to one mile, the frontage amounting to something over three miles. The area of the glacier is estimated at about two square miles. It lies mainly between 7,500 feet and 6,400 feet above sea level, the easternmost nose attaining the latter elevation, or about 400 feet higher than the Victoria.

2. Piedmont Type.

The peculiarities above noted in form are dependent upon the very unusual method of formation. Instead of there being a trunk stream, to which the minor ice streams are tributary, the entire glacier results from the amalgamation of twelve, more or less, independent ice streams, each with its own feeding ground, which lie side by side. There is no propriety in speaking of these streams as *tributaries;* but since they are all nourished from the same general source, the snow which falls upon the eastern slopes of the Ten Peaks, since they coëxist, are tolerant of one another's presence, and maintain their own identity and independent velocity from névé to nose, they may be spoken of as "commensal streams," to borrow an adjective from the biologists. The form of the front, the position of the medial moraines, and the névé areas enable us to differentiate these streams as shown upon the map, and less well in plate XXI. Owing to the general slope of the valley floor, the commensal streams are deflected eastward, their natural course being northward. However, it is quite apparent that they interfere with one another's movements. The easternmost stream is relatively very small, terminating back some 3,000 feet from the nose of its neighbor, where it is forming a terminal moraine. Its neighbor to the west is narrow, but in conjunction with streams three and four, counting from the east, it reaches the general front and together they form a broad rounded nose. Number five spreads out fan-like at its lower end, and in consequence six and seven, in their lower third, are deflected rather sharply to the north. Streams seven and eight, from Mt. Deltaform, are exhibiting the greatest amount of relative activity. In the western part of the glacier the ice streams are turned eastward by the tremendous accumulation of morainic blocks which they are unable to push ahead or override. In consequence, number nine, which has only a limited collecting area, is considerably compressed, being forced laterally against its sturdier neighbor to the east. It is not likely that any one of these streams could exist by itself as an independent glacier, since it would flatten out, be more thinly clad with débris, waste more rapidly from surface and lateral melting, and disappear soon after leaving the shadow of the mountains.

This form of glacier is known as the "piedmont type," and, so far as the writer is aware, only one other example, the Malaspina, of Alaska, has thus far been

described. This has a breadth of 70 miles and an average length of 20 to 25 miles, with approximately 1,500 square miles of area. It is made up of four great commensal glaciers, with an innumerable number of smaller ones. Farther west there lies the Bering Glacier, known to be of the same type, but not yet visited and described. It is quite likely that this variety of glacier is more common than has been recognized, since in addition to the Wenkchemna there is the Horseshoe Glacier at the head of the adjoining Paradise Valley, with some 16 commensal streams, and the Asulkan in the Selkirks (plate XXXIX, figure 2) which represents a piedmont glacier in process of disintegration into its component streams. If the ordinary Alpine glacier, with its tributaries, is compared to a river, the body of a piedmont glacier should be thought of as an ice *lake*, of greater or less magnitude.

3. Nourishment.

Each of the component streams of the Wenkchemna may be traced back to a more or less well defined and fairly distinct patch of névé. This may be no more than a cone of avalanched snow, or it may be a strip of permanent snow field filling a couloir in the mountain side, or between two adjacent peaks. The highest point of the Divide here is Mt. Deltaform, with an elevation of 11,225 feet, somewhat lower than Victoria. To the west, and closely connected with Deltaform, is Neptuak (Allen's No. 9) with an elevation of 8,767 feet. Eastward from Deltaform there occur in order No. 7 (10,648 feet), No. 6 (10,520 feet), No. 5 (10,018 feet) and No. 4 (10,028 feet). The northern face of this array of peaks is very abrupt, furnishing only a meager collecting area for the snow. The snowfall is probably not materially different from that at the head of the Lake Louise Valley, where it is estimated as about 25 feet annually. That which clings to the steep slopes during the winter is largely avalanched upon the glacier below in the spring and early summer. The most of that which remains is melted and but little survives the warm season. The snow accumulates along the northern base of the range, where it is protected from the noonday sun, allowing it to become converted into névé and compacted into ice. Owing to the increased altitude of the glacier's surface toward the west there is a greater deposit along the base of Deltaform and Neptuak (plate XXI). This rather meager supply of snow could support a glacier of such dimensions only because of certain favorable conditions. Being in the lee of some 3,000 feet of nearly vertical cliff, its névé field is sheltered from the noonday sun, while that portion which is exposed is almost completely veneered with a protective covering of rock débris. The form of glacier, with the ice streams lying side by side, reduces the lateral melting to a minimum, while the slope of the valley floor, upon which the glacier rests, is sufficiently gentle to allow the ice to remain in a very sluggish condition.

4. Drainage.

Because of the conditions just outlined the amount of ablation is reduced to a minimum and the surface drainage streams are correspondingly small and

FIG. 1.—Drainage brook from Wenkchemna Glacier, August, 1904. Free from sediment and having a summer temperature of 35° to 36° F.

FIG. 2.—General view of eastern end of Wenkchemna Glacier, August, 1904. Looking southward. The very complete covering of rock débris and irregular surface are well shown.

inconspicuous. Some near the center have cut their way a few feet into the ice. None of them reach the margin of the glacier, but find their way to the base through crevasses, or moulins. Opposite peak No. 7 a small stream of pure water from the valley enters the side of the glacier. The drainage from the Wenkchemna Lake, which collects the waters from the base of Mt. Hungabee, reaches the glacier through the great accumulation of morainic blocks (plate XXIV, figure 3). No surface lakelets were observed upon the glacier, although numerous depressions occur, suggestive of the former sites of lakelets. The water is probably lacking now because of the small amount of surface melting. There was practically no marginal drainage observed. At the east end, between the side of the mountain and the glacier, there occurs a small lakelet and opposite Mt. Deltaform, at the front, there is a very shallow lakelet, or marsh, of insignificant proportions.

The various subglacial drainage streams are collected beneath the glacier into a single stream which gushes from the extreme eastern compound nose and cascades over the coarse blocks of the frontal moraine in several channels. These form a single broad drainage brook (plate XXIII, figure 1), about 100 feet across, shallow and rapid, which enters Moraine Lake one-half mile below, dropping 210 feet in the distance. The volume could not be measured, but was estimated at about 90 cubic feet per second, being somewhat in excess of the volume of the Victoria drainage brook. The volume did not fluctuate during the day nearly so much as is usual for glacial brooks, suggesting that the supply is not so dependent upon immediate melting of the ice. This is further indicated by the temperature of the water, which remained during the middle week in August very steadily at 35.6° F., and rarely varying more than 0.2° to 0.3°, no matter at what time of the day taken. September 8, 1905, it was still 35.6° at 12:30 P.M. A surprising feature of the brook is its remarkable freedom from glacial sediment, the water issuing from the glacier perfectly pure. Flowing over coarse gravel and boulders it acquires no sediment upon the way to the lake and has formed not even the suggestion of a delta at the head of Moraine Lake (plate XXV). This indicates that the subglacial erosion is practically nothing and has remained so for centuries, testifying to the sluggish condition of the glacier. In flowing the half mile to the lake the temperature of the water in August was raised from 35.6° to 36° or 37°. The lake is about a mile long, has an elevation of 6,190 feet, is apparently shallow, and filled with the purest water of an intense blue color. Passing the length of the lake the temperature in August is raised to about 44° F. The freedom of the water from sediment permits it to exhibit its natural color, a simple glance at which, as far away as the color could be distinguished, enables one to safely predict the absence of sediment from the brook emptying into the lake. Should the glacier become active and start to erode its bed the color of the lake would change to some shade of green.

5. Moraines.

Except for the comparatively narrow strip of névé along the base of

the cliff, well seen in plate XXI, the entire upper surface of the glacier is veneered with angular rock débris, effectually preventing surface melting, as already shown. This material is derived from the Wenkchemna group of peaks, through the agency of avalanches and the ordinary processes of weathering. With the entire breadth of the glacier spread out along the base of the cliff all portions receive their quota, leaving no portion of the ice exposed to the sun. The débris, at first, is covered with the snow, but it is concentrated by melting until the amount is sufficient to prevent further loss of ice at the surface when the action ceases. No ground-morainic material was observed upon the surface, in contrast with the Victoria, and this is accounted for by the absence of hanging glaciers. What might be mistaken for such upon the northern face of Mt. Deltaform, and upon either side of peaks 4 and 5 (plate XXI), are simply the continuous névé fields of the commensal streams. This method of acquiring its load leads to a somewhat irregular distribution of the rock débris, resulting in hummocks and depressions, especially towards the northeastern corner (plates XXI and XXV). These irregularities of surface are also shown in plate XXIII, figure 2. It was from this portion of the glacier that the view for plate XIX, figure 1, was taken. This irregularity of surface renders travelling across the glacier laborious and somewhat dangerous, except near the névé line. The almost complete concealment of the ice by débris renders this glacier a poor one for the study of ice structure and the usual surface features. The third ice stream, coming from between peaks 5 and 6, in the vicinity of the névé shows stratification and dirt zones to advantage, the strata ranging from five to ten feet in thickness. Low glacial tables occur here and the phenomenon described upon page 58 of this report, as possibly due to reflection of heat from the surface boulders.

The line of junction between neighboring ice streams is roughly indicated upon the surface by ridges of rock débris, somewhat low and poorly defined near the névé, but gaining in height and distinctness in their course across the glacier. These ridges are the lateral moraines of the individual ice streams and they are especially well defined over the eastern third of the glacier. Upon either side of the third stream these ridges are double for a considerable distance. Toward the western end of the glacier these moraines are neither so well defined nor so continuous and, owing to the deflection of the streams to the eastward, by the ancient moraine, swing around into a position almost parallel with the frontal. By the blending of these lateral moraines upon adjacent streams the single ridges resulting become the medial moraines of the piedmont glacier, and the outermost laterals of the two marginal streams become the laterals of the unified glacier. At the eastern end of the glacier the first stream is so short that the right lateral of the second ice stream constitutes the right lateral of the glacier as a whole. If the first stream ever extended to the front then this lateral moraine was originally a medial. A deep depression, snow-filled in 1904, separates it from the double débris cone and from the mountain spur shown upon the map. At the western side of the glacier, owing to the deflection eastward of the ice streams, there is no distinction to be made between

the lateral and the frontal moraine. They end in a peculiar series of short closely pressed ridges, slightly concave outward.

Since a glacier of this kind cannot be said to have an *end*, the term frontal may be more appropriately applied to the rock débris that is being dumped along the united extremities of the individual ice streams. Were the glacier to begin a uniform retreat from its present position, there would be left a ridge of angular rock débris, over three miles in length, marking the shape and present position of the front. Inside of this would be left upon the valley floor the débris which now mantles the surface of the ice, or is contained within. Because of the very slow advance, to be noted below, the frontal morainic material over the eastern half is being very slowly urged forward, giving a steep and unstable frontal slope, but not so steep that it can not be climbed at almost any point. At only one point, nearly opposite peak No. 7, is there any ice showing and here the débris cover is partially lacking. Should the ice front actually halt a frontal moraine would form very slowly, in spite of the amount of débris carried, because of the sluggish condition of the ice. Toward the western side the front becomes less steep and high and finally merges into the névé and snow bank which mantles the col between Neptuak and Hungabee.

6. Crevasses.

The glacier is remarkably free from crevasses in the lower part and about the sides. In the case of the commensal streams, measurements would probably show that the sides were moving forward at about the same rate as the centers, so that there is lacking that differential movement that gives rise to marginal crevasses. The mutual pressure from the sides is sufficient to prevent the opening of radial crevasses along the front. The absence of prominent transverse crevasses indicates that the bed is of even slope and the motion slow enough to allow the ice to yield, without rupture, to most of the inequalities that do exist. The absence of crevasses in this case is quite as instructive as their presence would be. Upon the steeper portions of the névé slopes there occur numerous transverse breaks of the nature of *bergschrunds*, caused by the upper mass clinging, for the time being, to the rocky wall while the lower portion draws away from it. If kept under inspection these schrunds would be found to close up, as they work their way down the slope and to open again at a higher level.

7. Movement about the Front.

In a little booklet prepared for the Canadian Pacific Railway by Messrs. George and William Vaux, and entitled *Glaciers*, attention was first called to the evidence that this glacier is advancing into the adjoining forest. No data were at hand for determining the amount of this forward movement, or whether it is still in progress. Dead trunks of forest trees, from which the bark and branches have fallen, are seen projecting from near the frontal slope (plate XXIV, figure 1). Some of these trees were probably killed by a forest fire

which swept through the valley 70 to 80 years ago. Other trees in similar position, but also dead, still retain their bark and boughs, but show no signs of fire. It is likely that these trees were killed, and more or less displaced, by the advance of the ice front (plate XXIV, figure 2), since which time the ice has advanced less than a dozen feet. This is still further evidence of the almost stagnant condition of the glacier. Only at one point, near the center, were there any trees which have been recently cut by rolling blocks from the frontal slope. This is taking place about the nose of the stream coming from Mt. Deltaform.

In order to gather some definite data concerning the frontal movements, a series of eight sets of reference blocks was established along the eastern half of the front, beginning at a point just east of the drainage brook. Between certain marked points upon boulders that had rolled forward and others firmly embedded in the frontal slope, accurate measurements were made with a steel tape. From August 9 to September 12, 1904, an interval of 34 days, it was found that there was no perceptible movement at the station east of the drainage brook. Passing westward along the front, and up the valley, the data indicated that there had been a wastage of the ice, causing the blocks to settle back 1.2 inches and 0.7 inch. The next two stations showed an advance of 1.9 and 1.3 inches, while the next two gave a retreat of 1.0 and 4.6 inches respectively. At the upper station, where the trees had been freshly cut, the advance for the 34 days amounted to 11.8 inches. One year later, September 8, 1905, measurements were again made between the series of blocks and at all of the stations (the upper block at station D could not be located because of disturbance) there was a small advance indicated, varying from 1.7 inches to 20.4 inches. The least movement was about the extremities of the easternmost streams and the greatest was towards the center.

A summary of the measurements is given below.

Stations.	Movement for 34 days, Aug. 9 to Sept. 12, 1904.	Movement for 361 days, Sept. 12, 1904, to Sept. 8, 1905.
Á	0.0 inches	1.7 inches.
A	−1.2 "	2.4 "
B	−0.7 "	4.8 "
C	1.9 "	12.0 "
D	1.3 "	Missing.
E	−1.0 "	3.2 "
F	−4.6 "	20.4 "
G	11.8 "	15.1 "

These figures indicate that the component glaciers are as independent in their movements as in their structure, and that some may be stationary, or in retreat, while others lying alongside are advancing. The question of the frontal behavior of a piedmont glacier is thus seen to be complicated in proportion to the complexity of its structure. Measurements made at single stations can give only very incomplete data concerning the glacier as a whole. There should be at least one such measurement for each commensal stream.

8. Former Activity.

a. Bear-den moraines. Along the western front of the Wenkchemna, for a

FIG. 1.—Front of Wenkchemna Glacier, showing its encroachment upon the forest. August, 1904.

FIG. 2.—Front of Wenkchemna Glacier, showing recent forest invasion. September, 1905.

FIG. 3.—Disintegrated sandstone blocks of ancient "Bear-den moraine," Wenkchemna Glacier.

FIG. 4.—Melted area upon the *north* side of surface block of gray quartzite, Victoria Glacier, August, 1904.

distance of over a mile, there occurs a tremendous accumulation of huge morainic blocks of a red and brown sandstone. The blocks are much disintegrated by the weather, and falling apart, but each roughly indicates its former size and shape (plate XXIV, figure 3). Near the upper end of the valley the moraine is a half mile across, extending from the glacier to the foot of Eiffel Peak and almost completely surrounding Wenkchemna Lake, as shown upon the map. Toward the east the moraine becomes narrower and there may be distinguished an older portion, partially soil-covered and forested. These latter blocks are more completely coated with lichens and have plainly the appearance of greater age. There is thus evidence that the moraine was formed at two different periods, the older portion surrounding the lake and extending eastward, and that a considerable interval, as expressed in years, separated the two periods. Opposite peak No. 7 there occurs at the front an accumulation of coarse blocks, evidently part of the younger of the two ancient moraines, which the present glacier has been able to partially override. Farther west the glacier has been unequal to the task of either pushing the blocks ahead or of overriding them, and the streams have been deflected eastward, as previously noted. When the formation of the older of the two moraines began the glacier reached across the valley and deposition started. The glacier had so little depth, owing to the meager supply of névé, that it was unable to heap the blocks into a great ridge. Apparently the rather thin edge of ice was pressed against the moraine and there melted by pressure, and the blocks deposited along the southern margin until a belt a quarter mile in breadth was formed. A considerable period intervened during which time the eastern portion of the glacier had shrunken to much smaller proportions than it had formerly held and than it has at present. In a manner still to be accounted for, the glacier a second time became loaded with very coarse blocks and started to advance, possibly because of the protection afforded the surface by this load. Encountering the former moraine, however, it was unable to go over, or around, and it used its energy in a vain attempt to push the obstacles ahead. The pressure exerted caused the melting of the ice and the blocks were deposited in another broad, continuous belt, parallel with the first. As though it had learned wisdom by the experience, the glacier now rather calmly turns eastward and passes around the obstruction which it has built in its own path. These two moraines, lying side by side, are of the same type as the two described in the Lake Louise Valley, and, as far as may be judged roughly from their general appearance, of approximately the same age. The cliff from which the material was obtained has a west-northwest trend and the blocks were dropped from it to the eastward.

b. Moraine Lake. This lake has had a different history from that of Lake Louise in that it is apparently not a rock-basin and so attains no great depth. It is, however, like Lake Louise in that it has a morainic dam across its foot, although in the case of Moraine Lake the dam is of a different type. This consists of a sharply defined heap of rock débris about 400 feet long, placed at right angles to the main axis of the valley. The ridge increases in height

rather gradually toward the west and attains a height of about 70 feet, ending abruptly, as steeply as the débris will stand and with no trace of any continuance across the valley. This is so unusual a feature for a terminal moraine that many are disposed to consider the mass as a rock slide from the adjoining mountain face. There are several varieties of rock represented in the heap and time did not permit an examination of the adjoining face to see whether they might have had such a source. The strata in the region, however, are so nearly horizontal that, whether the feature is a moraine or a slide, the same rocks probably occur in the adjoining mountain as farther up the valley. Standing upon the highest crest, the ridge is seen to be double, the outer one somewhat convex down stream, while from the western end there passes a short spur down the valley. The writer is disposed to accept the view of Wilcox, who gave the name to the lake, that we have here a moraine. It is, however, not of the bear-den type found farther up the valley, but very much older than the most ancient of the two. Its general lack of vegetation may be due to the scarcity of suitable soil, although it does support a sparse growth of timber. The unusual features of the mass, considered as a moraine, will be understood when the unusual nature of the glacier that formed it is considered. This represents the position of the front of the easternmost ice stream, of the ancient piedmont Wenkchemna during a prolonged period of the halt. This moraine originally abutted against a wall of ice at the west end, the side of the adjacent ice stream, which probably extended far down the valley and may have been engaged in making a correlative moraine. A relatively small amount of the débris was dragged for a short distance down stream by this neighbor, forming the spur above noted. When this ice wall melted away finally the débris rolled down and assumed the "angle of repose." As has been pointed out the present easternmost stream is short, compared with its neighbor, and were it to make a sufficiently prolonged halt there might be produced, upon a smaller scale, this identical feature.

c. Valley of Ten Peaks. The time that could be devoted to this glacier did not permit of an examination of the valley from the lake to the Bow River, or of the interesting Consolation Valley, which still supports a glacier at its head. Observations of only a general nature from the elevated trail around Mt. Temple could be made. There is evidence that the entire valley was occupied by a great ice stream, a tributary of the trunk glacier that filled the Bow Valley, the glacier then being of the Alpine type. The lower half of the valley was altered by the ice into the characteristic U-shape, while the upper half retained its flaring side walls from pre-pleistocene time. In making the bend from its east-southeast course to the northeast, the glacier pressed hard against the western face of Mt. Babel, while upon the opposite, or concave, side there was deposited a high ridge of ground-morainic material which swings around in a very regular curve from the Eiffel to Mt. Temple. From the northeastern shoulder of Mt. Temple there extends into the Bow Valley, curving gently down stream, a spur of ground-morainic material, identical with that described for the Lake Louise Valley upon page 8. This was deposited beneath the ice and along the line of junction of the

General view of Moraine Lake and eastern extremity of Wenkchemna Glacier. Published here through the courtesy of the Detroit Photographic Co.

Map of Yoho (Wapta) Glacier, head of Yoho Valley, Canadian Rockies. Surveyed and drawn by W. H. Sherzer, August, 1904. Field assistants De Forrest Ross and Frederick Larmour.

ancient Wenkchemna and Bow glaciers. Looking down the valley towards the Bow, Babel Mountain is on the right and Mt. Temple upon the left, rising above the high morainic ridge mentioned. From the shoulder of Mt. Temple there extends to the center of the view the morainic ridge reaching out into the Bow Valley, gradually losing in height and breadth. As pointed out by Wilcox, this deposit probably mantles a rock spur which escaped destruction by the ice. During the height of glaciation a tributary glacier moved in northwestward from Consolation Valley and joined the Wenkchemna at a level 400 to 500 feet above the present valley floor, forming a "hanging-valley." From the "Tower of Babel" there curves across the mouth of the valley what appears to be a morainic ridge, of the same nature and origin as that just described. The height of this hanging-valley above that of the Ten Peaks is believed by some to measure the differential erosion between the ancient Wenkchemna and that of the tributary which occupied this valley.

CHAPTER V.

YOHO GLACIER.

1. General Characteristics.

This glacier, the largest and most northerly situated of the series studied constitutes a tongue of ice from the great Waputik snow-ice field which mantles the Continental Divide to the north of the railway. Its nose lies in latitude 51° 34′, at the head of the picturesque Yoho Valley, and is most conveniently reached from Field, via Emerald Lake. The day's ride, over a fairly good trail, up this ice-cut valley, with its hanging glaciers and plunging cataracts, is an experience never to be forgotten. The return trip to Field should be made over the Burgess Pass. During the summer the Canadian Pacific Railway maintains a camp at Laughing Falls, some four miles from the glacier. The glacier was first made known through the descriptions and photographs of Jean Habel,[1] secured in 1897, and each summer since it has been visited by gradually increasing numbers of tourists and students. The original name was derived from the Wapta River, another name for the Kicking Horse, the name "wapta" itself meaning river in the Stoney Indian language. The name Yoho since approved by the Canadian Geographic Board is the Indian exclamation of surprise and wonderment.

As one emerges from the forest and comes suddenly face to face with the glacier, plunging at him from above, he is greatly impressed with its size and apparent power. Its freedom from surface débris better enables it to meet the popular idea of what a glacier should look like,—the Victoria and Wenkchemna, having been somewhat disappointing (plate XXVII, figure 3) in this respect. The Yoho has the general form of a gauntlet mitten, extending in a south-southeast direction, with the *thumb* upon the eastern side of the valley and partly surrounding a great rock embossment (see plates XXVI and XXVIII, figure 2). Independently of

[1] "The North Fork of the Wapta," *Appalachia*, Vol. VIII, No. 4, 1898, pp. 327–336.

its névé it is three miles in length and for its upper two-thirds nearly one mile in breadth. In rounding the rock embossment noted it narrows to a half mile and then tapers regularly to a blunt nose. The mean elevation of the névé, according to Wheeler, is 8,400 feet, and the nose descends to an altitude of 5,670 feet. By noting the temperature of boiling water, Habel determined this elevation at 5,680 feet. The nose of the Yoho is thus 330 feet lower than that of the Victoria, and 730 feet lower than the Wenkchemna, in spite of the lack of débris covering and the southerly exposure. This is due, without doubt, to the greater precipitation and the greater size of the collecting area, by which a much larger body of ice is amassed. The mean average slope from the névé to the nose is about 900 feet to the mile; the main part of the descent, however, is in the lower half. The general inclination of the ice about the front is 20° to 25°. Upon the western side the glacier presses more or less firmly against the valley wall, except for a short distance, where the ice is steep and not to be ascended without cutting steps. By crossing the drainage stream, which is not a simple proposition unless one is mounted, one may easily ascend the glacier without the cutting of steps, the ice slope being very gentle. Skirting the crevasses and crossing back to the west side of the glacier, the névé may be easily and safely reached. Since its discovery by Habel, the glacier has maintained a great archway of ice at its lower extremity, which spans 250 feet of space, and is estimated to be 70 feet high, from which escapes the drainage. Owing probably to its southern exposure there is formed a cavern beneath the arch, as seen in plate XXVII, figure 4, extending back into the ice 100 to 200 feet, but not forming a subglacial tunnel. Toward the close of the summer season, the arch has become so weakened by melting and the formation of a transverse crevasse (plate XXVII, figure 3) that the entire structure collapses and lies a heap of azure ruins. The blocks of ice are melted down to a size that the stream can push, roll, or float, some head being obtained for the stream by the damming action of the ice débris. Finally it is all removed and the making of a new archway is started.

The actual nose of the glacier lies to the east of the archway and rests upon limestone bedrock, with only a sprinkling of ground-morainic material. Upon either side, and for some distance beyond the nose of the glacier, there is bedrock exposed, which has been smoothed in places by previous ice action and in other places roughened by plucking. Upon the western margin of the drainage brook there are shale strata upon edge which have been thus roughened. Excessively thin laminæ alternate of an intense red and yellow color. There are no reliable data for estimating the thickness of the ice, but it seems to be considerable. In the case of the Victoria and Wenkchemna glaciers the most conspicuous geological work being done is *transportation*, in the case of the Yoho we have very plainly a great engine of *erosion*.

2. NOURISHMENT.

The collecting area of the Yoho is triangular in outline and includes the region between Mt. Collie (10,315 feet), Mt. Baker (10,441 feet), and Mt. Gordon (10,336

feet), the sides of which triangle are approximately 3 x 4 x 5 miles (plate XXVIII, figure 2). The area is located upon the western slope of the Great Divide, the crest of which extends in a curve from Mt. Baker to Mt. Gordon. The collecting area is estimated at about 6½ square miles. Upon the western slope of the Divide it presumably receives more precipitation than falls in the Lake Louise Valley and that of the Ten Peaks. From the meager data available at Field we calculated that the precipitation may amount there to 42 inches per annum, page 11. To the north it would be somewhat less and may be assumed to be 40 inches. Over the névé area the great bulk of this would fall as snow, but that which was precipitated as rain would be absorbed at once and rendered available for the glacier, representing about 33⅓ feet of snowfall each year. This amount over the collecting area, the region in which the snow is manufactured into glacial ice, would represent some 224 million cubic yards of snow, or about 24,396,000 cubic yards of ice, available each year for the Yoho. If our assumed data are approximately correct, this must represent the amount of ice to be disposed of annually by melting and evaporation. Converted into water, this volume of ice would produce 22,372,000 cubic yards of water, or 604,032,000 cubic feet of the same. Distributed over the months May to September inclusive, during which time the melting is most active, this would give an average flow of about 46 cubic feet per second. During midsummer the flow is probably four or five times this amount, due largely to the fact that the actual area drained is much larger than the single névé field, and that the melting is now at a maximum. The névé coming in from the eastern, or Mt. Gordon side, as well as that from the western or Mt. Collie side, has already been compacted into glacial ice before reaching the main flow from Mt. Baker. This ice is incorporated into the Yoho névé with whatever débris it may be carrying. The absence of overhanging cliffs about the névé area, quite in contrast with the Victoria and Wenkchemna glaciers, prevents the névé snow from becoming charged with rock débris. The glaciers from the slopes of Gordon and Collie, as well as the main stream from Mt. Baker, are carrying only subglacial material, of which we have evidence later. To this is to be ascribed the freedom of the glacier from surface débris. This condition of the ice, combined with its southern exposure to the sun, is unfavorable to the maintenance of a glacier at low altitudes. This is entirely obviated, however, by the greater bulk of ice available when this glacier is compared with the two previously described.

3. Distributary.

Except for the névé-covered glaciers above noted from Mts. Gordon and Collie, the Yoho has no tributaries; but instead, what has been termed a *distributary*, to assist it in getting rid of its ice supply. A considerable volume of ice is deflected around to the eastern side of the rock embossment and is there prematurely melted. (See plates XXVI, XXVIII, figure 2, and plate XXVII, figure 3.) This tongue of ice forms a very pretty little glacier, one-half mile long by one-quarter mile broad and tapering down to a blunt nose (plate XXVII, figure 1).

The surface is soiled with wind-blown dirt but it carries little débris. At an earlier stage it brought down from above the left lateral morainic material for the Yoho, and its ice extends still well under this ancient moraine. The axis of the glacier is curved as it is forced around the rock embossment, which it hugs closely and is still engaged in fluting and polishing (plate XXVII, figure 1). The upper crest of the rock embossment has an elevation of 6,960 feet, while that of the nose is 6,320 feet, or 650 feet above that of the main glacial stream. The average slope would be at the rate of about 1,300 feet to the mile. It is evidently in retreat although no data are available for determining the rate. In the upper portion of its course, it appears to descend over a steep step in its bed and is much crevassed. These crevasses completely heal, however, or are destroyed to their bases by melting, leaving the lower half exceptionally smooth. Over this portion of the small glacier there are developed three very pretty drainage systems, two of them marginal and the third central. The central drainage, which is collected into a trunk stream (plate XXVII, figure 1) from a network of small tributaries, has cut a longitudinal channel in the ice, and continues to a point just east of the nose. Habel's map of the Yoho Glacier shows this tongue of ice continuous around the rock embossment, forming of it a rock island, or so-called "nunatak." Such a position it originally held, but not less than 200 years ago, so far as we may judge from the size of trees growing in the valley. At a still earlier stage of glaciation the entire embossment was overridden by the ice, much of it being disrupted, wherever the ice could get a satisfactory grip upon the strata. The resistant portions were planed down, rounded, and fluted.

4. Moraines.

Because of the lack of overtowering cliffs, above noted, the general surface of the Yoho is practically free from coarse rock débris, in striking contrast with the Victoria and Wenkchemna. For the same reason also the lateral moraines are poorly developed and almost absent in the lower half mile. Upon the western margin, just before reaching a broad glaciated valley, originally carrying a tributary, the right lateral moraine begins to make its appearance and develops across the mouth of the valley into a well defined ridge of stony till, or ground-morainic matter. This ridge is continuous up the slope to the line of junction of the main Yoho with the glacier from the eastern slopes of Mt. Collie, where the latter is seen to be delivering this material from its under side to the surface of the Yoho. This ground moraine has been produced between the Collie Glacier and its bed, frozen into the ice, and urged down the slope.

The left lateral moraine begins along the southern side of the rock embossment, down in the valley, as a double ridge from which the ice has been withdrawn. It extends around the embossment, on the west side, for a distance of some 4,500 feet, developing into a prominent, high, sharp-crested ridge at the head and curving across to the eastward. This consists, also, almost entirely of ground-morainic matter, which must have been derived from the basal layers of the ice, which became stranded at the head and about the west side of the rock emboss-

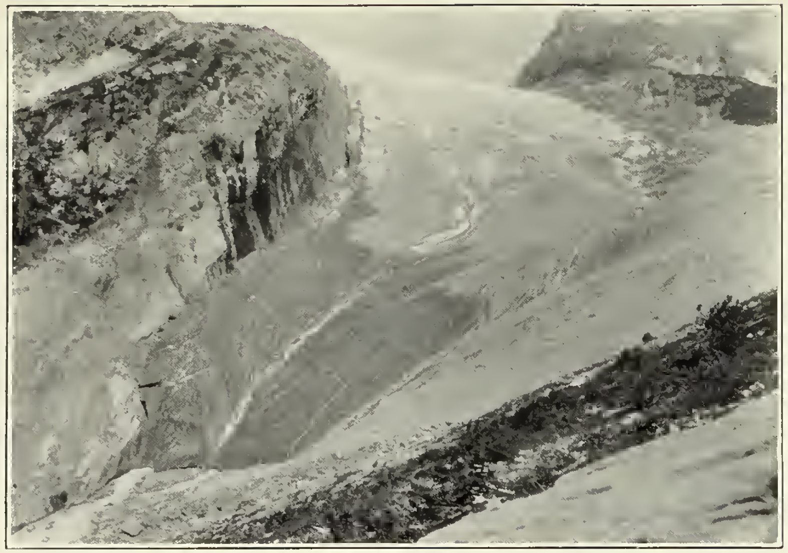


FIG. 1.—Ice distributary from Yoho Glacier.

FIG. 2.—Ice "plucking" upon a mountain peak, head of Yoho Valley.

FIG. 3.—Yoho Glacier, head of Yoho Valley. Photographed by De Forrest Ross, August, 1904.

FIG. 4.—Three-hundred-foot ice arch, Yoho Glacier, from which issues the Yoho River. Photographed by De Forrest Ross, August, 1904.

ment. In the valley occupied by the distributary described, and from 600 to 700 feet down from its nose, there begins a second lateral which curves around upon the débris-covered ice and continues for two miles along the shoulder of Mt. Gordon. This portion of Gordon has an elevation of 9,510 feet, but its cliffs do not overhang and contribute only a moderate amount of material to the moraine. A considerable portion of it consists of ground moraine which may be traced to the glacier from Mt. Gordon. This sustains the same relation to the Yoho as does the Collie Glacier upon the opposite side of the valley. Up to heights of 30 to 40 feet patches of morainic material can be seen upon the valley wall, left there when the surface of the glacier stood at a higher level. The rocks in the moraine are largely limestone, light and dark, yellow and mottled; some pieces being oölitic.

An older lateral moraine, upon the eastern side of the valley slope, may be traced for some 2,000 feet up the valley from the nose. The ridge is some 200 to 300 feet from the margin of the ice, is but three to four feet high and inconspicuous, but it has heaped promiscuously over it a mass of broken tree trunks very evidently brought down by an avalanche and heaped against the side of the ice when it stood here. The distance from the margin of the ice to the ridge, at one point, was found to be 260 feet, along the slope. The wood is somewhat decayed and gives some appearance of age. A photograph was taken when the trunks were covered with a light fall of snow, which had melted from the surrounding rock, rendering them much more conspicuous than they would otherwise be with their dark surroundings. Growing in the path of the avalanche trees were found, the largest of which gave 25, 28, and 47 rings respectively. It is likely that the avalanche occurred between 1850 and 1860, since which time the glacier has been retreating down the slope at the average rate of 5 to 6 feet per annum.

With so little rock débris carried upon and within the glacier it would require a very prolonged halt of the front in order to build up a terminal moraine of any considerable proportions. About 200 feet from the present nose, at the end of the bedrock upon which it rests, there swings in from the side a weakly developed double ridge, low and inconspicuous. It may be the correlative of the lateral moraine above noted, carrying the avalanched timber, or it may mark a still more recent halt in the general retreat. Within recent time the glacier has deposited very little ground moraine, the conditions not being favorable for its lodgment. The lowermost stratum shows upon the western side of the drainage stream, beneath the archway, and is seen to be charged with débris. Much of this is delivered to the stream and swept away by the swift current, the remainder being spread thinly over the valley floor.

5. Crevasses.

Opposite the head of the rock embossment described, the glacier and its distributary plunge over a steep step in their beds, of which the embossment itself is probably a portion which the glacier was unable to reduce to the general level

of its bed. In making this rapid descent the ice is crevassed both transversely and longitudinally. The irregular blocks of ice formed melt into sharp points, or steeples, to which the term "seracs" is applied. The transverse crevasses have been noted which open just behind the archway at the nose, allowing the arch to collapse toward the close of the melting season. The absence of pressure in front allows the arch to drop forward, faster than the ice can yield to the tensional strain, and the crevasse is the result. Along both margins, for nearly the entire three miles, the normal lateral crevasses, described for the Victoria, occur. They extend inwards and upwards for varying distances, are irregularly spaced and become less numerous toward the névé, where some of them are snow-filled and snow-covered. In passing the ice cascade the ice is too much shattered to permit the formation and preservation of the dirt bands described upon page 52 of this report. However, at the crest of one of the minor slopes the phenomenon may be seen, as shown in plate XXIX, figure 1, where the depressions for three bands are plainly marked out. These mark the sites of former crevasses, and, if rightly interpreted, the distances between them show the approximate annual motion at this portion of the glacier.

6. Ice Structure.

In both the main glacier and the distributary the stratification of the ice is poorly preserved, possibly because of its destruction in passing the cascade. General views, as well as detailed ones, give almost no trace of the strata. In plate XXVII, figure 4, one stratum, relatively much charged with débris, forms the base of the arch, but does not appear upon the opposite side. This basal stratum where seen is 2 to 5 feet in thickness. Its upper surface may represent a shearing-plane, the body of the stratum being held more rigidly by its content of débris while the superincumbent ice is forced over it.[1] In places where the strata are still preserved, the dividing planes show poorly, and it is to be noted that this may arise because of the paucity of foreign material concentrated at the upper surfaces of the strata. In the case of this particular glacier the size of the névé field precludes any but the finest dust from reaching the general surface, and with so few peaks uncovered in the region the supply of dust must be meager. No opportunity was afforded for observing the structure of the névé itself. As pointed out by Reid, in the paper cited upon page 43, the basal layers of a glacier may be able to pass a cascade without suffering destruction, while the upper strata may be destroyed and in large part melted away. This may be the cause of the poor development of strata in the case of the Yoho, and the absence of the dirt zones, which should show especially well over the smooth lower half of the distributary.

In spite of the almost complete obliteration of the strata in the upper part, the blue bands are shown in great perfection where the ice presses against the west valley wall. The edges run parallel with the margin and the bands dip

[1] "The Influence of Débris on the Flow of Glaciers," I. C. Russell, *Journal of Geology*, vol. III, p. 823, 1895.

down into the ice at angles of 42°, 48°, 53°, 54°, 56°, and 61°. Upon the walls of the crevasses they may be seen to curve around into a position parallel with the valley floor. At the surface the position and approximate thickness of the bands are indicated by the dirt stripes. Differential movements of the ice, after the formation of the bands, have given rise to curved, twisted, and contorted patterns in numerous places towards the center (plate XIII, figure 2).

The fine development of glacial granules and capillaries in the Yoho Glacier has been already noted upon pages 39 and 41. They here attain the largest size of any seen in the series of glaciers studied and appear to have about the same amount of orientation near the nose.

7. Drainage.

Owing to the crevassed condition of the main glacier, there is little opportunity for the development of surface drainage streams, the water soon making its way to the bottom of the bed. In the upper portion where the crevasses are not so numerous toward the center, there seems to be too little melting to call for much surface drainage. The drainage upon the distributary has already been referred to. There enters its side a strong flow of water from the hanging-valley to the east (plate XXIX, figure 2), derived from the glaciers lying between Mt. Balfour and Mt. Gordon. Opposite the head of the rock embossment there is a short strip of marginal drainage as shown in the map, but the stream is small and the flow weak. Upon the opposite side of the valley two streams with a brisk flow enter the side of the Yoho from the broad, glaciated valley noted, while a third flows down the northern slope from the glacier upon Mt. Collie. Marginal or surface lakelets were nowhere observed. Augmented with the flow from the hanging valley, there rushes from beneath the nose of the distributary a torrent of slightly turbid water, which flows for 4,000 feet over the débris-strewn floor and enters the side of the Yoho. At the upper end of the line of avalanched wood described, this stream has cut a gorge, 40 to 50 feet deep, across a ridge of limestone strata. The gorge extends beneath the present margin of the ice and, in all probability, has been cut very largely under subglacial conditions, this part of the valley being under ice when the distributary completely encircled the rock embossment. This stream flows for 1,600 feet beneath the ice of the lower Yoho and contributes the bulk of the water which issues from the cavern at the nose, the North Fork of the Kicking Horse.[1] This stream, although shallow at first, is rapid and has a breadth of 240 feet, spreading over the gravel flat with a network of channels. About one-quarter mile from the exit the channels are collected into a single one, forming a river of very respectable size, considering its youth. The water is somewhat turbid, but much less so than that which ordinarily issues from the Victoria. This is because the drainage from the glacier itself is so largely diluted with that from the adjoining valleys, derived in considerable part from the simple melting of snow and carrying a minimum of sediment. Owing to the volume and velocity of the stream, much of the rock

[1] Marked Yoho River upon the latest maps of the Canadian Topographic Survey.

débris is carried and rolled down the valley. The channel beds are lined with coarse rounded boulders, making the fording of the stream, afoot or mounted, somewhat difficult, especially after a day of rapid melting. In the early morning the volume and velocity are somewhat reduced.

The dilution of the Yoho drainage, with that from the adjoining valleys, raises the temperature, as was noted in the case of the Wenkchemna drainage brook. The last two weeks of August the temperature ranged from 33.8° F. to 35.2° and gave an average of 34.7°. Opposite the Takakkaw Falls, about five miles from the nose, the stream has descended 770 feet and its August temperature has been raised from three to four degrees. At Field the temperature of the Kicking Horse, August 23, 1904, was found to be 44.2° F. at 5:15 P. M. On August 30, 1905, at 6:30 A. M. it was 39.6°.

8. Frontal Changes.

In August, 1901, reference marks about the nose of the Yoho were independently established by Miss Vaux and Mr. H. W. Du Bois, from which it was determined in 1904 that the glacier had receded, in the three years, a distance of 111 feet (August 16, 1901 to August 18, 1904), or at the average rate of 37 feet a year. Measured to the block of ice which had until very recently constituted the nose, the distance was 92.1 feet, of which 23 feet was for the year 1903-4, reducing the average to about 31 feet for the three years. Between August 18, 1904, and August 31, 1905, the retreat was found to have been but 9 feet. The average annual retreat for the four years 1901 to 1905 has been 30 feet. At a second station upon the western side of the drainage stream the retreat from August 17, 1904, to August 31, 1905, was 4.6 feet. From these meager data it seems that the Yoho is having its retreat checked.

9. Former Activity.

a. Moraines. Lack of time prevented any careful survey of the entire Yoho Valley from the glacier to where the valley joins that of the main Kicking Horse. No coarse moraines of the type described for the Victoria and Wenkchemna were seen and their absence is easily accounted for by noting the absence of steep cliffs about the glacier and its névé fields, plate XXVIII, figure 2. In passing up the valley the trail crosses two steep ridges, densely covered with vegetation, but these appear to be of the nature of mountain spurs, or rock slides, from the western side of the valley. About 1,000 feet from the present nose there is an interesting display of modified ground moraine, lying mainly upon the eastern side of the stream (plate XXVIII, figure 1). The structures consist of low knolls and crescentic ridges, connected with the weak lateral moraines by faint ridges. Six series may be made out, concentrically placed and with their convexities directed down stream, diminishing in height and distinctness toward the glacier. The ridges vary in height from one to twelve feet, the longest being in the form of a semicircumference with a radius of twenty feet. The ridges possess the smooth, rounded outlines of drumlins, but lack their profile

FIG. 1.—Knolls and ridges of ground-morainic material in front of Yoho Glacier. Suggestive of frontal moraines of latest ice sheets in North America and Europe.

Collie. Baker. Gordon. Balfour. Waputik snowfield.

FIG. 2.—General view looking up Yoho Valley, showing Wapta and Waputik snowfields. Photographed, 1904, by Arthur O. Wheeler, from summit of Mt. Wapta (9,960 feet). Looking north-northwest.

FIG. 1.—Formation of Forbes's dirt bands from crevasses, Yoho Glacier, August, 1904.

FIG. 2.—Hanging Valley, head of Yoho, lying between Mts. Balfour and Gordon. August, 1904.

and arrangement. They are like drumlins in that they consist of ground-morainic material, with but a thin dressing of gravel and sand. They differ essentially from drumlins in that their longer axes are parallel with the former ice margin, instead of at right angles to it. If composed of stratified sand and gravel they would be kames. In short they have the structure of *drumlins* and the form and position of *kames*. They so much resemble in miniature the knolls and ridges formed by the last great ice sheet in its retreat from the United States and Germany that their origin becomes of especial interest. They have evidently been formed by the glacier, with its nose consisting of a series of lobes, plowing into the ground moraine previously deposited upon the valley floor. A retreat occurred and then an advance, falling a little short of the first position, by which a series of mounds and curved ridges was pushed up. This was repeated at least a half dozen times, each advance being somewhat weaker and falling a little short of the preceding. Finally the glacier advanced over the entire series, but overrode them so lightly that instead of being destroyed they were simply smoothed and rounded. In melting back the last time, either from the ice itself, or from the subglacial drainage, or from both sources combined, a thin layer of sand and gravel was deposited over the structures. Had the ice lobes been larger the ridges would have appeared more nearly straight, as we find them in the case of the Pleistocene deposits.

b. Plucking action. About the nose of the glacier, as has been already noted, and upon the eastern side, toward the rock embossment, there are numerous illustrations of the bodily disruption of the rock strata, to which the term *plucking* is applied. Conditions are most favorable for this action when the strata are thin bedded and jointed, when the strike of the strata is transverse to the glacier and the dip is down stream. Under these conditions the rock layers are ripped off and the bed lowered with relative rapidity, the rock fragments being pressed into the ice and moved forward to assist in further work of a like nature. In this way portions of the bed are much *roughened* by ice action, instead of being smoothed. The edges and corners of the strata which were able, at the last, to resist the action of the ice will be found to be rounded more or less. A mountain spur, lying between the nose of the glacier and Mt. Balfour was overridden by the ice and experienced this action upon an extensive scale. The mountain is made up of curved, concentric strata, the upper layers being of a dark limestone. Upon the southern side these layers dip to the southwest at an angle of about 30°. In passing over the peak from north to south many feet of strata have been removed, those able to resist the action forming a succession of steps upon the steeply inclined slope. One only of these steps is shown in plate XXVII, figure 2, behind the hard crest of which the loose fragments have collected, while upon either side they have been swept clean by the ice. This furnishes an illustration of what is known as a "knob and tail" phenomenon. If the combined height of the successive steps were ascertained we should have a figure representing the minimum amount of this plucking action upon the southern

slope, if not over the crest of the peak. It is well to note that this was done with a relatively thin sheet of ice, while in the valley bed, with some 3,000 feet additional of ice thickness, the result, under equally favorable position of the strata, would have been correspondingly greater. It seems very probable that the peculiar form of the peak Trolltinder (9,414 feet), just south of Balfour (plate XXVIII, figure 2), is due to similar plucking action.

c. Yoho Valley. There is abundant evidence that the entire valley, from the Kicking Horse at Field, was occupied by an immense ice stream, seventeen miles in length, which served as a tributary to the ancient Kicking Horse Glacier, of Pleistocene time. It, in turn, received short tributaries from the adjoining valleys and mountain slopes. The valley was filled with ice to a depth of 1,500 to 3,000 feet above the valley floor, by which the lower portion was transformed into the characteristic U-shape, seen best from below. When viewed from a height as in plate XXVIII, figure 2, the more flaring walls of the upper portion become the more conspicuous. The valley seems to have had the same general history as that given for the Lake Louise district, page 61. Being a longitudinal valley of the Rocky System, it was originally a trough between mountain folds, or a great crevasse, which collecting the drainage of the region was cut into a V-shaped valley by the joint action of running water and the weather. With the coming of the glaciers, the valley was occupied by ice and the lower one-third to one-half deepened and broadened, while the upper portion, as high as the ice could operate, was simply smoothed and subdued. Spurs were cut off and faces exposed to the action of the ice were grooved and fluted, polished or scratched.

A series of typical hanging-valleys occur along the Yoho beginning with that of the distributary, the floor of which is not yet uncovered. This ice stream has not been able to lower its bed as rapidly as has the main Yoho, and when melted back to the head of the rock embossment there will be exposed a side floor at a higher level than the main floor. However hanging-valleys, in general, may arise, this one seems certainly due to the differential effect of the two streams upon their respective beds. To the right of the distributary there extends a hanging-valley to the northeastward between Mts. Gordon and Balfour, still occupied by two glaciers, which appear to have built conjointly a double frontal moraine (plate XXIX, figure 2). This valley has a double floor, of which time did not permit an examination. From the photographs taken there appears to be a lake, occupying a rock-basin upon the lower level. About 3½ miles down from the nose of the Yoho the Twin Falls drop into the valley from the floor of a hanging-valley coming in from the west. The falls are 310 feet in height, but their crest (6,500 feet) is 1,050 feet above the floor of the main valley opposite. Five miles down from the glacier are seen the Takakkaw Falls, in the center of plate XXVIII, figure 2, the crest of which is 1,200 feet above the valley floor. The valley floor from the glacier to these falls descends about 770 feet, or at the average rate of 154 feet to the mile. These figures, based upon data supplied by Wheeler, indicate that the main valley has been lowered from 1,000 to 1,200 feet more than the tributary

Map of Illecillewaet Glacier, Illecillewaet Valley, Selkirk System. Surveyed and drawn by W. H. Sherzer, September, 1904. Field assistant Frederick Larmour. Elevations from A. O. Wheeler.

valleys. With the effect in mind of relatively thin ice sheets upon the neighboring peaks, the writer is quite prepared to admit the sufficiency of glaciers to produce hanging-valleys, when the ice is deep, concentrated, and operates for a long period over stratified formations.

CHAPTER VI.

ILLECILLEWAET GLACIER.

1. General Characteristics.

Passing from the Rockies westward to the Selkirks, we find much evidence of the increasing precipitation; one of the first to which our attention is unpleasantly called is the tantalizing number of snow-sheds which obstruct our view. The mountains are much more completely forested than we found them in the Rockies and nearly everywhere the valley slopes are scarred with avalanche tracks. From extensive snow-fields (plate XXXII, figure 1) hundreds of tongues of ice descend to much lower altitudes than is possible in the Rockies, with their slighter snowfall. The largest of these ice tongues to be seen from the railway is the so-called "Great Glacier," or Illecillewaet,[1] the glacier that gives rise to the "rushing water." Owing to the ease with which it may be reached from the station it has been visited by more people than any other glacier in the two Americas, although, so far as known, it was not seen by the eye of white man until the year 1883. In that year it was discovered by Major Rogers, who was in search of the railway pass which now bears his name. It was originally named Agassiz Glacier by Ernest Ingersoll,[2] but this name has since been transferred to one of the commensal streams of the great Malaspina, in Alaska.

The glacier lies just to the south of Mt. Sir Donald (10,808 feet), between it and Glacier Crest, and as a great tongue of ice spills over the rim of the extensive collecting basin enclosed between Mt. Sir Donald, Mt. Macoun (9,988 feet), Mt. Fox (10,572 feet), and Mt. Lookout (8,219 feet). See maps, plate XXX and XXXIII. The glacier flows to the northwest, is but $1\frac{1}{3}$ miles in length, and in this distance tapers from a mile in breadth to a sharply pointed nose. The axis of the glacier is slightly curved, with its convexity turned toward the southwest. Lying in a broad valley with this exposure, and with no covering of débris, the glacier receives the full effect of the noonday and afternoon sun. In spite of this the nose attains the altitude of 4,800 feet, or 870 feet lower than the Yoho. Since the collecting areas are very similar in size, this difference must be due mainly to the differences in the amount of snowfall received by the two regions. The latitude of the nose of the Illecillewaet is 51° 15′, being nearly a third of a degree farther south than the Yoho. From the névé line, with an elevation of about 7,500 feet, the glacier descends 2,700 feet to the nose, or at the rate of about 2,000 feet to the

[1] This name is pronounced as though it were spelled *Illy-silly-wet*, with the stress upon the middle syllable.

[2] "The Rocky Mountains as Seen from the Canadian Pacific Railway." *Science*, vol. VII., 1886, p. 243.

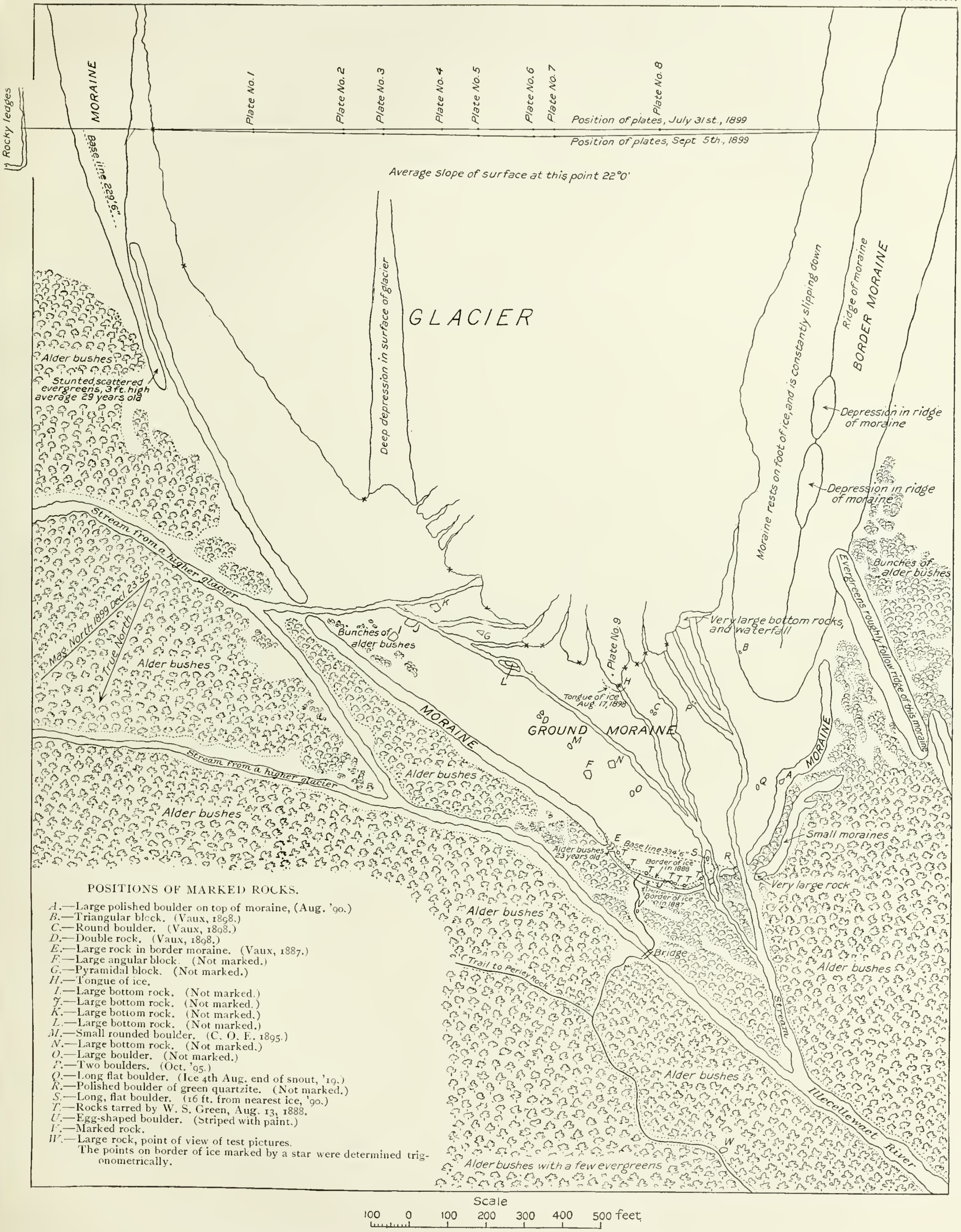
mile. The greater part of this drop is in the upper half, the glacier descending from the rim of the basin in a steep cascade, by which the ice is shattered and its original structure destroyed (plate XXXII, figure 2). In its short length the glacier receives no tributaries, but instead has a series of short distributary noses perched high up along the eastern line of cliffs leading to Perley Rock (plate XXX), with elevations ranging from 6,450 feet to 7,000 feet. No data exist for estimates upon the thickness of the glacier, but the greatest thickness of ice probably occurs below the crest of the cascade and may amount to several hundred feet.

The marginal ice is very steep upon the eastern side and for a quarter of a mile back from the nose upon the western side, so that it can not be easily ascended. Toward the nose the general inclination is about 30° to 35°, diminishing to 20° and less, so that one may mount the glacier from the nose for a short distance. The névé may be reached by a rather rough climb, either around to the east by Perley Rock, or by ascending to the depression between the glacier and the steep left lateral moraine, keeping a sharp lookout at first for rolling rock from the eastern face of the moraine. About the main nose, upon the eastern side, there occur a number of minor noses, shown in plate XXX and plate XXXII, figure 2, and also a sharply defined, trough-like depression in the surface of the ice, from 200 to 300 feet across and tapering up stream for a considerable distance. This depression appears in all the photographs taken since 1887 (plates XXXVI, XXXVII, figure 2), since which date about 400 feet of the floor immediately beneath it have been uncovered without disclosing any cause for the depression. In plate XXXII, figure 2, it appears to be continued up the glacier to the cascade and may have its origin there in some obstruction of the bed by which the ice is diverted to either side and left thinner in the lee. Just to the left of the nose there has been uncovered, since 1898, a mass of bedrock for a distance of 400 feet, its more rapid radiation of heat accelerating the melting of the ice resting upon it. The rock consists of a brownish, schistose conglomerate, furnishing an interesting display of glacial features to be described in another section of the chapter (page 95). This is the only bedrock observed in the floor of the valley from the glacier to the station.

2. Nourishment.

Meteorological data at the station of Glacier House are, unfortunately, very meager. The average precipitation for the five years available amounts to 56.68 inches, of which 43.7 inches (36 feet and 5 inches), or about 77 per cent. of the whole, fell as snow.[1] Over the névé region practically this entire amount would be available for glacier formation and, as snow, would represent about 47 feet. The retangular snow-field extending from Mt. Sir Donald to Mts. McCoun and Fox is about five miles long, by two miles broad, and hence contains about ten square miles of collecting area (plate XXXIII). Of this area about two-thirds, or six to seven square miles, drains northward and feeds the Illecilliwaet, while the remainder moves southward and nourishes the Geikie Glacier, which

[1] *The Selkirk Range*, A. O. Wheeler. vol. I, p. 414.



Tongue and Moraines of the Illecillewaet Glacier, August, 1899. Published through the courtesy of George and William S. Vaux, Jr. From the Proceedings of the Philadelphia Academy of Natural Sciences, 1899.

flows westward between the Asulkan and Dawson ranges. The collecting basins for the Illecillewaet and Yoho glaciers are almost equal in size, but the estimated precipitation over the former is 41 per cent. greater than over the latter, giving a correspondingly greater volume of ice to be disposed of. This enables the Illecillewaet to attain a much lower altitude, as previously pointed out.

The mean elevation of the surface of the névé lies between 8,000 and 8,500 feet above sea level; ranging from 7,500 to 9,500 feet, not essentially different from the Yoho névé. In the central portion the névé is much crevassed, from which one may infer that the thickness of the snow and ice is not great in the basin. The surface is covered with parallel ridges and furrows, probably resulting from the rippling action of the wind while the snow was being deposited. These ridges when frozen render the walking somewhat difficult and treacherous.

3. Moraines.

a. Surface débris. Because of the wide extent of the névé field and the absence of precipitous cliffs about the margins, there is very little opportunity for the névé to acquire any rock débris. There is no evidence that any considerable quantity is gathered from the bed and carried subglacially, or englacially. It may be that the basal layers in the névé region are sluggish, or even stagnant, and that only the upper layers are being pressed out over the rim of the basin. The result of this lack of débris in the névé is that the general surface of the glacier, as in the case of the Yoho, is unblemished with rock fragments, but is somewhat soiled from wind-blown dust concentrated over its surface by melting. Some dust wells occur sparingly and a few poor examples of glacial tables.

b. Left lateral moraine. Along the western margin of the glacier fed by the ordinary atmospheric agencies of rock decay operating upon the cliffs of Glacial Crest and Mt. Lookout, there has been built up a high, sharp-crested, left lateral moraine. The angular rock fragments are supplied mainly by two prominent débris cones, which have formed upon the eastern face of Glacier Crest and which rest with their bases upon the margin of the ice, the forward movement of which has distorted the cones down stream, plate XXXII. In the summer rocks may be seen coming down these slopes, one block starting others and these still others, until a regular cannonading is in progress. As one rock collides against another with terrific force, small clouds of dust arise and we have simulated not only the roar but the smoke of battle. John Muir has given us a graphic description of the streaks of fire to be seen when these avalanches occur at night. In the way previously described for the Victoria (page 47) this material arranges itself in the form of a sharp-crested ridge perhaps 100 feet above the margin of the ice and 150 feet above the valley floor. The melting of the ice core upon the inner slope makes it steep and unsteady, while the outer has settled into a condition of more stable equilibrium and is being slowly covered with vegetation. Upon the inner slope occasional slides of the rock veneering occur, by which the ice core is temporarily exposed. The materials from the upper part and sides of the scar produced roll and slide down, collecting

at the bottom and growing slowly upward until the ice is again completely covered. In this way the material is being more thinly spread over the morainic ice core and its melting accelerated. The great height which the moraine has been able to attain in its lower part is due to the fact that the glacier is unprotected by débris over its general surface, and the differential melting is so much greater than it would be if the surface of the ice were protected as in the case of the Victoria.

The material of which this moraine is composed is principally quartzite and a silvery (sericitic?) schist, with a binding of glacial sand and clay. Occasionally boulders are scratched, and are very generally bruised, with their edges and corners rounded from rough treatment they have received upon the débris cones and the moraine. About one-third of the distance along this moraine there occur two elongated depressions, exactly in the crest of the moraine. The larger and better defined of the two is 125 by 50 feet and 6 to 8 feet in depth (plate XXXII, figure 2). They are seen from a distance most plainly when the sun's rays strike somewhat obliquely, permitting the sides to cast shadows into the bottoms of the depressions. Attention was first called in print to these depressions by the Vaux Brothers in 1900,[1] showing very plainly as they do in their early photographs. Before these depressions were visited it was thought by the writer that they might represent the sites of drained lakelets, similar to those found upon the Victoria, but the explanation suggested by the above investigators seems to be the correct one. The moraine appears to have been formed of two ridges, laterally welded together, and these depressions appear to be spaces left where the two ridges did not quite meet. Owing to the sliding of the débris upon the inner slope of the moraine the basins are being obliterated and will eventually completely disappear.

Including the débris cones this lower portion of the left lateral is some 4,000 feet in length, rises to less and less height above the general ice level, and gives out for a short distance, where the ice abuts directly against the quartzite cliffs of Glacier Crest. Up to a height of 40 to 50 feet patches of morainic matter have lodged upon the rock shelves. One-quarter mile beyond, a crested ridge again makes its appearance composed of materials derived from Mt. Lookout, just to the southeast. The moraine is largely made up of quartzite and schistose boulders bound together with sand and clay and supporting a sparse growth of mosses and Alpine plants. The ridge rises to a height of 35 to 40 feet above the ice, curves around to the eastward, becomes reduced in height, and disappears under the névé, which is strewn with rock fragments derived from the cliffs of Mt. Lookout.

c. Terminal moraines. From the lower extremity of the left lateral there curve around into the valley two lower ridges, of the nature of terminal moraines. The inner and younger of these forms an inconspicuous ridge, from 6 to 10 feet high, and passes into the terminal moraine at which the glacier was found to be

[1] "The Great Glacier of the Illicilliwaet," George and William S. Vaux, Jr., *Appalachia*, vol. IX, 1900, p. 164.

Sir Donald. Illecillewaet Glacier. Asulkan Glacier. Mt. Bonney and glaciers.

FIG. 1.—General view of peaks and snowfields from Rogers Peak (10,536 feet), Selkirks, looking southeastward. Photographed in 1902, by Arthur O. Wheeler.

Illecillewaet névé. Asulkan névé.

FIG. 2.—General view of Illecillewaet Glacier from summit of Mt. Eagle, elevation 9,353 feet, distance two to three miles. Photographed in 1903 by C. F. Johnson.

standing in 1887. From their photographs taken in this year the Messrs. Vaux have established the position of the ice front with reference to a very large boulder resting upon this moraine. This terminal ridge swings around to the north and connects with the right lateral, which is of greater age and, in the lower part at least, has lost its ice core. See plates XXX and XXXI.

d. Right lateral moraine. The ice has withdrawn from this moraine a distance of 400 to 500 feet, leaving a somewhat subdued boulder slope and a low ridge. This becomes higher and steeper as we approach the quartzite cliff which intercepts it about one-half mile back from the nose. Here the moraine is double, an older one lying just outside and parallel with it. Forest trees have taken possession of the crest and outer slope. The rocks in the right lateral are similar to those in the left and are found to be in the same condition of being rounded and bruised. Upon the rocky ledges, which carry the distributary noses referred to, there is spread out more or less morainic material, some of which has been assorted by running water. These ledges of quartzite have been much glaciated, plucked and extend up toward Perley Rock (7,898 feet). For about a quarter of a mile there extends an upper double moraine to the southeastward, where it disappears under the snow. The material consists of rounded boulders of quartzite and chloritic schist, with a filling of glacial sand. An inspection of the map shows that there is a correspondence in the arrangement and position of the lateral moraines; there being in both cases, a higher and a lower portion, separated by quartzite ledges, carrying only a sprinkling of morainic material. Since the cascade in the glacial stream lies between these exposures of quartzite it is probable that the ledges are continuous beneath the glacier; that they have proven too hard for the glacier to remove, and so it is compelled to cascade over them.

e. Boulder pavement. Between the terminal moraine and the present nose of the glacier there has been uncovered since 1887 a broad boulder belt, about 500 feet across. This consists of ground-morainic material in large part, with the rock fragments which were carried englacially, or supraglacially, and deposited as the ice front receded. These boulders have been overridden by the ice so lightly that they have not been disturbed, and yet a number of them were glaciated while in their present position, forming what is known as a "boulder pavement." About the present margin of the ice, boulders are being continually uncovered which are being subjected to the same action. The ice presses against the up-stream face of the boulder, and, either because of the warmth of the stone, or more probably because the melting point of the ice is reduced by the pressure, or because of both these agencies, an inverted trough, or fluting, is produced upon the under surface of the ice, having the form of the rock. In plate XXXIV we have these flutings shown in different stages of formation; in the last case (figure 2) the stone was estimated to lie 70 feet back from the ice margin and was under probably 50 feet of ice. Photographs taken some years ago of the "ice grotto" show that it was a feature of this kind produced by an unusually large rock. If the pressure were sufficient, the ice would settle in promptly upon the lee side

of the boulder and it would be glaciated not only upon the stoss and upper surface, but upon the lee side as well. A certain relation must exist between the extent of lee-side glaciation and the thickness of the ice, which, if known, would give some data for estimating the maximum thickness of certain Pleistocene sheets.

4. Crevasses.

The crevassed condition of much of the névé, especially that in the main direction of flow, has been noted. Faultings and dislocations occur, disclosing the stratified nature of the névé and subjacent ice. This crevassing is due, apparently, to irregularities in the bed, rather than to differential motion, and indicates that the ice here attains no great thickness. About the margin of the névé field there occur, here and there, breaks where the névé has withdrawn from a portion still clinging to the rocky wall. These are the *bergschrunds* described upon the Victoria and Wenkchemna glaciers (pages 22 and 67). On a line between Perley Rock and the western end of Mt. Lookout, there opens up a series of transverse crevasses as the ice begins its descent into the valley and its velocity is accelerated (plate XXXII, figure 2). The ice is unable to yield to the tensional strain and forms long V-shaped gashes at right angles to the stress. These become convex down stream because of the more rapid central movement of the ice. Conditions are here favorable for the formation of Forbes' dirt bands (page 50), but the ice soon plunges over the quartzite ledges, is shattered in every direction and all structure lost. Upon the crest of the cascade a network of crevasses opens, dividing the ice into irregular angular blocks. These become melted upon all sides and assume the form of pinnacles and steeples,—*seracs*,—displaying beautifully the stratified structure of the ice (plate XXXV, figure 2). Reaching the bottom of the cascade these blocks are jumbled together, many of them completely melted and the remainder frozen together into a great ice conglomerate (plate XXXV, figure 1). As pointed out upon page 44, it is quite conceivable that some of the basal layers might be able to descend the slope without having their structure destroyed.

The rapid central movement of the ice, due to the high average slope of the bed, gives rise to a very complete system of marginal crevasses, extending inward and upward, and showing conspicuously when the glacier is seen from a height. In the lower third the ice does not feel the restraint of the valley walls, spreads laterally because of its own weight, and there are opened longtitudinal and radial crevasses, some of them extending to the margin of the ice. As the surface is continually lowered by melting, only the bottoms of some of the shallower crevasses remain, and these appear simply as short gashes in the otherwise smooth surface.

5. Ice Structure.

There is evidence upon the glacier's left, back a short distance from the nose, that the stratification in the basal portion of the glacier is not completely destroyed in passing the cascade. Traces of the stratification may be seen dipping

Map of the Selkirk snowfields and glaciers, by Arthur O. Wheeler. Reproduced through courtesy of Canadian Topographic Survey, Department of the Interior. Approximate scale 1 inch = 1½ miles. Contour interval 100 feet. Reference datum mean sea-level.

FIG. 1.—Beginning of subglacial fluting by pressure-melting, Illecillewaet Glacier, August, 1905.

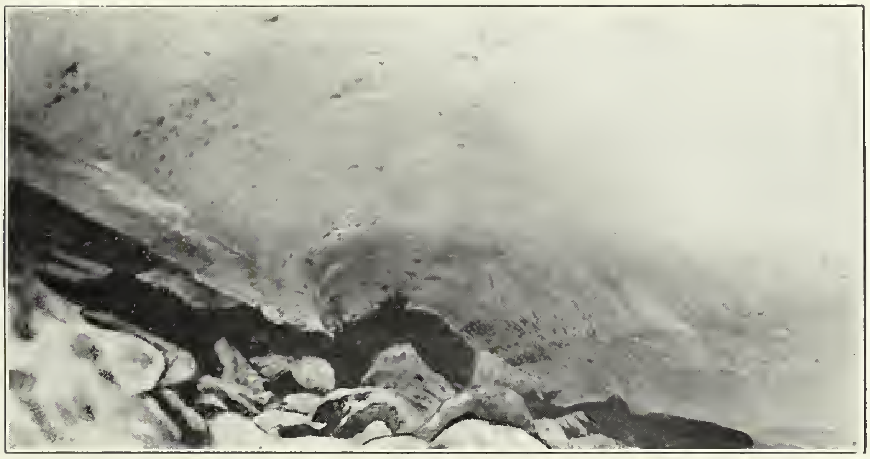


FIG. 2.—Subglacial fluting by pressure-melting, Illecillewaet Glacier, August, 1903. Photographed beneath the glacier and at an estimated distance of 70 feet from the rock responsible for the fluting.

FIG. 3.—Roches moutonnées near nose of Illecillewaet Glacier. Motion of ice from right to left.

inward towards the center, this portion of the ice possibly having received less severe treatment than that nearer the center of the channel. In the case of the Yoho the question arose (page 76) as to whether the stratification was obscure because of its destruction by a similar cascade, or because of its original weak development. In the case of the Illecillewaet there is sufficient bare peak and rocky crest exposed to supply the broad névé field with successive layers of wind-transported dust and a very perfect stratification results from the concentration of this dirt at the surface of successive deposits (plate XXXV, figure 2). The almost complete lack of stratification about the nose, where it should be well displayed, along with the dirt zones, must in this case be ascribed to the cascade. The dust, originally concentrated between the strata, is brought to the lower margin of the ice, where it collects and drips as black mud (plate XXXIV, figure 1) over the valley floor. The color is due to the presence of organic matter, of which there is enough present to render the material offensive, when set away damp in a warm room. Four determinations of the organic matter present in material collected in 1903 gave 16.75, 11.25, 10.68, and 17.23 per cent., or an average of 13.98 per cent.

It seems impossible that the coarse stratification of the ice could be so completely destroyed and the finer lamination preserved so perfectly and continuously as we should have to suppose if we referred the blue bands to the original lamination of the névé. As pointed out upon page 44 and as shown in plate XIII, figure 1, the blue bands, with the superficial dirt stripes, are very clearly shown about the nose of this glacier, from 15 to 36 being counted within the distance of a foot. They are approximately parallel with the valley floor and would probably conform with the strata, providing the latter were present. They dip inward, in general, about the nose at angles of 3° to 8°, but in places are inclined outward by this amount. As soon as the ice begins to experience pressure from the moraines, or the valley walls, the blue bands become more and more steeply inclined, beginning with angles of 8° to 16° and increasing up the valley to 70° to 75°. The relation of bands in the ice to the stones which are fluting the under surface (plate XXXIV,) has been discussed upon page 44.

The glacial granules, with the melting phenomenon described in connection with the Victoria Glacier, are well shown about the nose. In size they stand next to those of the Yoho and range from the size of hickory nuts to that of hen's eggs. They are limited largely to the blue bands, or the white seams that intervene, but in cases are seen to cut across from one to the other. As the granules assume distinctness the blue bands become more and more obscured. Between the granules there is developed, under suitable melting conditions, a very perfect and beautiful network of capillaries described upon page 41.

6. Drainage.

a. Surface and marginal drainage. Upon the nights of September 7–8 and 8–9, 1904, the minimum temperature of the ice was measured by inserting a thermometer to the depth of twelve inches in the face of a crevasse near the nose.

The two readings were 32.0° F and 31.9°, indicating that this portion of the glacier was very near to its melting temperature. Before liquefication, however, can occur a large amount of heat must be rendered latent, when water is produced with the same temperature as that possessed by the ice just before melting. The heat necessary for this conversion is supplied in the main directly from the sun but in part by that of the atmosphere, rain, friction and pressure of the ice against the valley floor and sides, and whatever heat may be reflected, radiated, or conducted, from the same source. Almost without exception the surface drainage was found to have a temperature of 32°, varying but a very small fraction of a degree from this. The surface ablation is rapid during the summer, owing to the exposure of the ice to the sun and the absence of protective débris.

As would be expected from the greatly crevassed condition of the ice, no surface streams of any size can develop, either over the general surface or along the margins. Small streams flow directly to the ice margins and cut channels, in a few cases, to the depth of a foot. This water may be absorbed at once by the loose materials covering this portion of the bed, or it may collect and give rise to scant marginal or subglacial drainage streams. These flows soon cease when the sun drops behind Glacier Crest and throws the glacier into shadow. In 1904, for a distance of some 500 feet, a small drainage stream was found between the left lateral and the adjoining ice slope. Since the ice of the glacier is here continuous with the morainic ice core, this stream was a surface rather than a marginal one. From the lower end of this moraine there occurred also two small flows of water, apparently coming from englacial channels in the moraine. After a six hours' rain, September 8, 1904, during which 0.58 of an inch of rain fell, the water of these streams was rendered muddy, while the turbidity of the main glacial flow was not perceptibly affected.

b. Terminal drainage. Upon the eastern side of the glacier, drainage streams leave the ice margin in the neighborhood of the elevated distributary noses, as shown upon the map. The ice here rests upon bedrock and the streams have sought the lowest depression, there being three such which are draining this portion of the glacier. The westernmost of these breaks into a network of streams upon emerging from the ice, and cascading over the rocky ledges again enters the side of the glacier, to reäppear at the nose. The two other streams have cut gorges 50 to 60 feet deep across the hard strata, showing that they must have been at work for considerable periods, probably as subglacial streams. However, the high velocity of the water and the sharp glacial sediment enable it to work very effectively, even upon quartzite. These two cascade over the ledges and unite some 1,600 feet down into a single stream, which receives tributaries from the slopes of Sir Donald. Just outside of the right lateral moraine the stream divides into numerous branches, which reunite upon the gentle gravelly slope and form what is known as a "braided stream." Eastward of the upper, right lateral moraine, between it and Perley Rock, there is a deserted gorge, similar to those now being formed, partially filled with gravel and morainic matter. The drainage has been deflected westward to a lower level.

FIG. 1.—Regelation of ice blocks at foot of ice cascade, Illecillewaet Glacier, September, 1904.

FIG. 2.—Stratification in upper part of Illecillewaet Glacier.

In 1904 there issued from the main nose of the glacier five drainage brooks, the main one lying to the west of the nose and receiving the drainage from the left lateral moraine. This stream follows the inner curve of the terminal moraine and cuts across it at a point opposite the nose. The other four streams form a network over the boulder pavement, unite into a single stream, which makes its way across the terminal moraine and joins the main flow. About 1,200 feet from the nose of the glacier (1904) this drainage brook from the lower and west side of the glacier unites with the strong flow from the eastern side of the valley and together they form the Illecillewaet, or "Rushing Water," a tributary of the Columbia. The average flow from the glacier is not much different from that of the Victoria and Wenkchemna, but considerably less than that from the Yoho, which collects the drainage from a larger territory. Based upon the estimated size of the névé area and the average annual precipitation, the average flow for the months May to September, inclusive, should be about 65 cubic feet per second. Owing to the somewhat larger drainage area and the more rapid midsummer melting the flow seems greater than this in July and August. The water, as it issues from beneath the nose, is only slightly turbid compared with the Victoria, indicating a small amount of subglacial erosion. The color becomes slightly green in the combined streams and still more so after it has received the Asulkan drainage farther down the valley. With the loss of sediment, which is gradually stranded here and there, the water assumes a bluish tinge, except where lashed into foam.

c. *Temperatures.* During the last week in August and first week in September, both in 1904 and 1905, some 30 observations were made on the temperature of the drainage at the nose. The average temperature, taken at various times of the day, was found to be 33.1° F., with a range from 32.4° to 33.8°. That from the eastern side of the valley, taken just under the bridge on the trail, gave an average of 39.9°. One-third of a mile down the valley, at the lower bridge across the stream, the average temperature of the combined streams was 38.3°, ranging from 34.9° to 40.6°. Where the Illecillewaet passes beneath the railway, having received the Asulkan brook, four observations upon the temperature gave an average of 39.7 °.

7. Forward Movement.

As early as 1888 observations were made by Rev. W. S. Green to determine the forward movement of the glacier. On August 13, he set three poles in the ice by boring holes with an auger, the distance from the nose not being given.[1] These were visited upon the 25th of the same month and were found to have fallen, owing to surface melting. The holes were, however, found and the poles reset for measurement. The distances moved in the twelve days are recorded as follows: "No. 1 pole, near moraine, 7 feet; No. 2, further out, 10 feet; center of glacier, 20 feet." For the middle of the glacier this gives an average daily motion of 20 inches. About the margin of the ice Green, at the same time,

[1] Among the Selkirk Glaciers, 1890, p. 218.

tarred a number of boulders in closest proximity to the margin, which rocks could still be indentified in 1905. (See rocks marked T, plate XXXI.)

In 1899 George and William Vaux set a line of 8 steel plates across the glacier, some 1,400 to 1,500 feet back from the nose, their line lying somewhat obliquely to the main axis of the glacier (see map). The average surface slope was given as 22°, and the distance across the glacier along the line of plates was 1,720 feet. A base line was laid out along the higher portion of the right lateral moraine, 229.5 feet in length, and the plates located by triangulation, July 31, 1899. Bearings were taken upon the plates August 11, 1899, and September 5, 1899, the latter work being done by Messrs. H. B. Muckleston and C. E. Cartwright, of the Canadian Pacific Railway. One year later (August 6, 1900) the plates were again located by the Messrs. Vaux and their forward movement for the 372 days determined. The following table is based upon their data published in *Appalachia*, vol. IX, 1900, p. 160, and the *Proceedings* of the Academy of Natural Sciences of Philadelphia, March, 1901, p. 215.

TABLE VII,

OBSERVATIONS UPON THE LINE OF STEEL PLATES SET ACROSS THE ILLECILLEWAET GLACIER, JULY 31, 1899.

(Total Distance across Glacier along Line of Plates 1,720 feet.)

Plate.	Distance from East edge.	July 31 to Aug. 11, 1899.		Aug. 11 to Sept. 5, 1899.		July 31 to Sept. 5, 1899.	July 31, 1899 to Aug. 6, 1900.	
		Total motion, 11 days.	Average daily motion.	Total motion, 25 days.	Average daily motion.	Average midsummer motion, 36 ds.	Total motion, 372 days.	Average daily motion.
	Feet.	Feet.	Inches.	Feet.	Inches.	Inches.	Feet.	Inches.
1	265	3.54	3.86	2.62	1.26	2.56	88.6	2.86
2	500	3.33	3.64	8.67	4.16	3.90	124.0	4.00
3	605	6.25	6.82	8.75	4.20	5.51	139.7	4.51
4	750	6.21	6.77	——	——	6.77	181.0	5.84
5	845	5.96	6.50	11.71	5.62	6.06	188.0	6.07
6	980	6.37	6.96	13.79	6.62	6.79	197.0	6.36
7	1040	5.00	5.45	14.33	6.88	6.16	158.5	5.11
8	1310	5.50	6.00	——	——	6.00	170.0	5.48

An inspection of the above table shows that the maximum movement, for both the summer and the entire year, lies well to the west of the axis of the glacier. The greatest average daily movement was made by plate 6, which lies 120 feet to the west of the center, while plates 7 and 8 show only slightly less movement. This is in harmony with what is known concerning the flow of glaciers on a curve, the maximum movement taking place not at the center, as in the case of the very straight Victoria, but lying between the center and the convex side. The average daily movement of plate 6 for the year is 94 per cent of its summer motion, as compared with 81 per cent for the corresponding plate upon the Victoria. For some reason, not easily explained from the data at hand

the mean summer motion of the two most easterly plates was less than their yearly average. It is to be noted that the maximum summer movement of 6.96 inches (July 31 to August 11), 1899, is but about one-third of the maximum movement observed by Green in 1888 (August 13 to 25). The only way to reconcile the two results is to suppose that Green's measurements were made farther up the slope towards the cascade, where the movement is undoubtedly much greater than towards the nose. Messrs. Vaux placed a ninth plate upon the nose of the glacier and had it under observation from August 1 to August 20, 1899. The average daily horizontal motion for the first two intervals between measurements was 5.9 inches and 5.0 inches. A crevasse then formed, detaching the block carrying the plate, and the subsequent apparent motion was 2.8 inches and 2.7 inches daily.

8. Frontal Changes.

a. Recession data. Owing to the easy accessibility of the glacier and its attractiveness to the ordinary visitor, we have more data from which to determine the frontal behavior of the Illecillewaet than any of the other Canadian glaciers. As has been noted, from the photograph taken in 1887 by the Messrs. Vaux the position of the ice at that time, with reference to a large boulder, was determined and in 1898 marked conspicuously. In 1888 the margin of the ice was marked by Green and the glacier was photographed by Notman & Son, of Montreal (plate XXXVI, figure 1). Reference blocks were marked in 1890 and 1895 by interested visitors. A visit was paid to the glacier September 3, 1897, by Albrecht Penck, of Vienna, and a sketch made of the tongue of the glacier and its relation to the lower moraines. This was published in the *Zeitschrift des Deutschen und Österreichischen Alpenvereins*, Jahrgang 1898, Band XXIX, s. 55, under the title "Der Illecillewaetgletscher im Selkirkgebirge." The height of a number of points was determined by an aneroid and four reference blocks established and located upon the map. These blocks were left to be marked by a railroad employee, but were apparently neglected and in 1904 could not be identified with absolute certainty, owing to the changes in the ice margin. Based upon the railway elevation at the station, Penck determined the elevation of the nose in 1897 as 4,793 feet (1,461 meters). The foot-bridge, just beyond the modern terminal moraine he gives an elevation of 640 feet above that of the station, or above sea level 4,760 feet,[1] and this he uses as his datum for elevations about the glacier. The nose of the glacier at this time lay 33 feet above the floor of the bridge, and the crest of the adjoining lateral just opposite was 131 feet above the valley floor at the nose.

In the year 1898 a number of reference blocks and range lines were established by the Messrs. Vaux and have since done excellent service in measuring the frontal movements. In August, 1899, they made a very detailed survey of the nose and adjoining region and prepared a large scale map which is of the greatest

[1] The correction of the railroad levels reduces this elevation by 27 feet, giving the bridge-floor 4,733 feet.

value in the determination of changes in progress[1] (see plate XXXI). They have very carefully located upon their map the reference blocks established by themselves and others, so that they may be readily found upon the ground. To their untiring zeal and devotion to the cause we are very largely indebted for our knowledge of the behavior of the Illecillewaet front since the year 1887. From their reference blocks the writer took measurements in 1902, 1903, 1904, and 1905, and in 1904 established four other reference stations about the side from which to determine the marginal changes.

There is reason for thinking that the glacier in 1887 was just completing a rather prolonged halt at the younger of the frontal moraines described. That it had not recently extended much beyond is proven by the size of the alder bushes growing about the outer slope. That it had made a rather prolonged halt at this line, either at this stage or a previous one, is shown by the size of the moraine, which, with the small amount of débris carried by the glacier would require a considerable time in building. From the early photographs it is seen that the glacier was much bulkier and broader at this stage and the slopes about the nose much steeper, enabling the glacier to maintain well its position at the moraine (plate XXXVI, figure 1). During the year 1887 to 1888 it had begun to withdraw from the moraine, as shown clearly in the Notman view just referred to and as indicated by the rocks blotched with tar by Green. The retreat began somewhat gradually and attained its maximum between 1890 and 1900, averaging for these ten years about 53 feet per annum. The average for the opening lustrum of the century is 19.6 feet, the retreat being reduced until it amounted to but two feet for the year 1904-5. For the 18 years from 1887 to 1905, the horizontal retreat from the Vaux reference block was 597.5 feet, or at an average yearly rate of 33.2 feet. It should be noted, however, that this measurement is not in a line with the main axis of the glacier. The available data concerning this glacier are given in summarized form below. The measurements were taken variously, most of them between the middle of August and the middle of September, so that the retreat assigned to some years, may belong in part to the preceding, or the following year.

Recession Data of the Nose of the Illecillewaet Glacier.

1887–1888.	10 to 15 feet.
1888–1890.	Average rate about 23 feet
1890–1898.	Average rate of 56 feet.
1898–1899.	16 feet.
1899–1900.	64 feet.
1900–1901.	15 feet.
1901–1902.	48 feet.
1902–1903.	22 feet.
1903–1904.	11 feet.
1904–1905.	2 feet.
1905–1906.	84 feet.

[1] "The Great Glacier of the Illicilliwaet," George and William S. Vaux, Jr., *Appalachia*, vol. IX, Mch., 1900, p. 156.

FIG. 1.—Illecillewaet Glacier in 1888. Photographed by Notman & Son, Montreal.

FIG. 2.—Illecillewaet Glacier in 1905, from approximately the same view-point as figure 1.

Upon the face of the bedrock exposed near the nose a mark was established September 16, 1903, immediately beneath the nearly vertical side of the ice, the height of which was estimated as 60 feet. August 24, 1905, it was found that the ice had withdrawn laterally 2.4 feet from the face. Passing around from the nose eastward, three stations were established along the margin of the ice. A large boulder was found just emerging from the ice, the first week in September, 1904, and marked "Face emerging, Sep., '04." Upon the 24th of August, 1905, it was found that the ice had retreated here 14 feet. Farther along a medium-sized boulder had been marked in 1903, "15 ft. to ice. IX–16–03." By September 1, 1904, a retreat of 12.5 feet had occurred here, while at the upper station the boulder "27 ft. to ice. IX–16–03," measured September 3, 1904, 27 feet, and August 25, 1905, 27.1 feet. These data indicate that the margins of the ice have been receding as we approach the nose, more rapidly upon the eastern side, but that farther up along the margin there has been no change for the last two years and, very probably, for a considerably longer time The two views on plate XXXVI, taken from almost identically the same view-point, the former in 1888 and the latter in 1905, furnish a good opportunity for noting the changes produced in the glacier in the 17 years. It seems almost possible to recognize the individual trees standing to the right of the center, but the lower half of the glacier is unrecognizable. A stadia and trignometric survey of the Illecillewaet and Asulkan glacier tongues was made in 1906 by the Messrs. Vaux and a report made to the Philadelphia Academy of Sciences. Some additional data concerning the movements of the steel plates upon the Illecillewaet were collected and appear upon plate XXX of this report.

b. Ice waves. In comparing their photographs made in 1898 and 1899 from a certain large boulder, just west of the trail, Messrs. Vaux noted an apparent thickening in the ice just beneath the névé line. By drawing a delicate line between corresponding points in figures 1 and 2, plate XXXVI, that may be recognized in the upper névé region, it is seen that the ice margin along the sky-line stands slightly higher in the 1905 view. The difference is slight, however, and can represent but a few feet. When the Notman view of 1888 is compared with a second, which was made in 1897, and here reproduced in plate XXXVII, figure 2, the heaping of the ice line beneath the névé line is still more plainly seen. There is thus evidence that a wave, or impulse, derived from an increased precipitation over the névé region, travels the length of the glacier and gives rise to a halt, or an advance, of the front; followed by a depression which permits of a retreat. Such a depression appears to have been at the edge of the névé line in 1887 or 8, while the glacier about the lower extremity was experiencing the effect of a previous impulse. The retreat of the glacier was greatest between 1890 and 1900, and if we assume that it culminated at about the middle of the decade, it required about 8 or 9 years for this trough of the wave to reach the nose, or at the average rate of 800 to 850 feet per annum. Since in 1905 the appearance of the sky-line along the névé corresponds so nearly with that seen in 1888, we may assume that the crest of the wave was in this position at a date only a little later than the

mean of the two. This would bring it to about 1898 or 9, when it was especially noted by the Messrs. Vaux. The gradual reduction in the rate of retreat observed during the past three seasons would indicate that this impulse is making itself felt about the nose and that either a halt, or an advance, is about to be inaugurated. If we are correct in the inference that the névé line was marked by a trough, or low stage in the height of the ice, about 1887 or 8 and that a return to this condition has been reached about 1905 or 6 with a crest, or high-stage condition of the ice between, an interesting relation is at once established with Brückner's climatic cycle (page 16). The time between the appearance of these troughs for the passage of one-half of the wave is 18 years, and we may venture to predict that the present relative depression will be followed by the passage of another crest requiring about the same number of years. The nose has been in retreat from 1888 to 1906, some 18 years, and we should expect another period of halt or advance to soon set in. Such a condition was to be anticipated from the marked reduction in the rate of retreat from 1902 to 1905, but the very remarkable recession of 84 feet determined by the Messrs. Vaux for the year 1905–1906, leaves the matter in doubt.

The relation of the glacial movements to the precipitation cycles becomes a matter of much interest and here, as above, with our meager data, we can only point out possibilities, which will either stand or fall, when the next half-century's observations have been collected. From our available meteorological records there was a deficiency of precipitation over the mountains from 1885 to 1896; how much before 1885 this condition existed we have no means of knowing. Since 1897 there seems to have been an excess over the normal amount, but it was at this time that the crest of the wave made its appearance at the névé line. Then instead of continuing to increase, as we might expect, it gave way to a trough. The inference is, and it is only an *inference*, that this wave represents the gush of ice from the collecting basin due to the excess deposited during the phase of the cycle which antedated 1885, and probably to be correlated with the excess in the Rockies, as recorded so strikingly in the evidence of higher lake levels, described by Dawson (page 17). The approaching trough shown about the névé line in 1905 must then be ascribed to diminished precipitation received over the collecting region from 1885 to 1896, being then 9 years delayed from the close of the phase which gave rise to it. The crest of the wave from the basin was delayed some 17 to 18 years from the close of the preceding phase. In a paper read before the International Geographic Congress, at its Washington meeting (*Proceedings*, 1904, p. 487), Doctor Reid gave a discussion of "reservoir lag," in which he demonstrates mathematically that the thickening of ice in the collecting basin does not keep pace with the variation in precipitation, but lags behind it. In the case of large glaciers this lag amounts to about one-fourth of the period of the variation, and the ice in the basin should attain its maximum thickness, only about the time that the annual supply has settled back to the normal amount and is ready to diminish. After the maximum ice thickness has been attained toward the center, time is still required for the impulse to reach its maximum at the crest of

the basin, the amount of which will differ with the local conditions. In this way we may account for the delay in the arrival of the crest at the névé line in the years 1897–9.

9. Former Activity.

a. Rock scorings. The former work of the glacier is shown in great beauty and variety upon the mass of bedrock now being gradually uncovered near the nose. The hard rock features of Pleistocene glaciation are all here for study by those interested, many of them indicating the direction of ice movement and hence of practical value in the field.[1] Excellent examples of the so-called roches moutonnées occur, groups of which in the distance often resemble crouching sheep (plate XXXIV, figure 3). In the specimen figured, the ice moved from right to left across this projection of bedrock, the up-stream, or stoss side being rounded and smoothed, while the down-stream, or lee side, was affected slightly, or not at all. Portions of the rock were polished, as the ice was rubbed vigorously across, and where the ice held rock fragments against it, systems of approximately parallel scratches were produced, some so fine that they must have been made by sand grains. At the last stage of the disappearance of the ice from this particular roche moutonnée, a small clump of rock fragments was gently dropped upon the upper surface in insecure position. An inspection of this and the adjoining rock in the figure, shows a system of parallel joints, dipping down-stream at a steep angle. From the lee side of the central roche moutonnée it is apparent that an entire block was pried loose by the ice and that a little more vigorous action at the joint, just beginning to open, would have removed bodily nearly the entire block. This action is known as "plucking," already described in connection with the Yoho (page 79), by which the work done in a few days may exceed the erosion of years. Places may be seen upon the surface where a rock engaged in producing a shallow groove has made a succession of jumps and given rise to a series of short parallel curves, more or less closely placed, with their concavities directed down-stream. These are the "chatter-marks," the production of which may be illustrated by pushing a dry finger over a polished surface. In other cases rocks embedded in the under side of the ice have been suddenly brought into action, producing a crescentic gouge, with its convexity directed in the direction of flow.[2] The bedrock here being a schistose conglomerate with rather coarse, hard masses embedded in a softer matrix, there have been produced the "knob and tail," or "knob and trail" phenomena, so useful often in determining the direction of ice flow in the case of Pleistocene glaciers. In one case examined there appeared a dark colored knob of harder material, which the ice was unable to cut away as rapidly as the surrounding schist. The projecting knob had partially protected the softer material in its lee,

[1] A most valuable paper by Chamberlin upon the effect of ice upon rock will be found in the *Seventh Annual Report of the Director of the U. S. Geol. Surv.*, 1888, page 155.

[2] See paper by Gilbert read before the Cordilleran Section of the Geological Society of America at its 1905 winter meeting. "Crescentic Gouges on Glaciated Surfaces," *Bulletin Geol. Soc. of Amer.*, vol. 17, pp. 303–314.

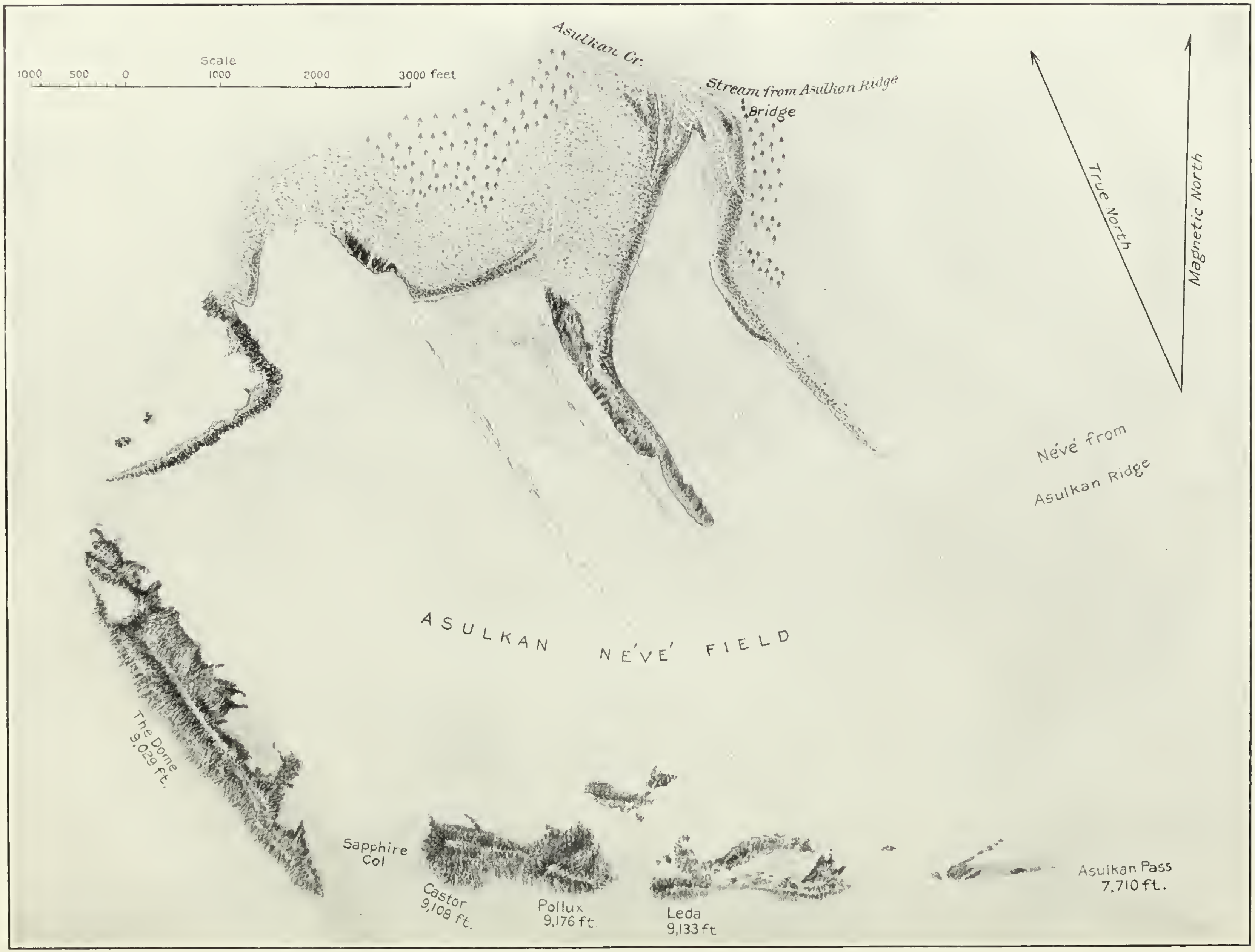
forming an elongated tail, or trail, extending from the knob in the direction of ice motion. In some cases a small quartz vein cuts across the surface in such a way as to protect in its lee a strip of the softer rock. In front of the knobs there is cut out, as a rule, a frontal groove lying at the base and curving around laterally into two others, one upon either side, forming the lateral grooves. In places where the ice acted with greater vigor, owing to the concentration of its action, or where differences existed in the structure, or hardness, of the rock there were cut out basins and U-shaped troughs, representing, in miniature, lake basins and glaciated valleys. One basin, with perfectly smoothed sides and bottom, had a length of 15 feet, a breadth of 6 feet, and a depth of 6 to 8 inches below its lower rim. The greatest depth was located one-third of its length from the upper end, indicating where the gouging action had been greatest. One of the troughs was 11 to 12 feet across and 4 to 5 feet in depth.

b. Bear-den moraines. Some 800 to 900 feet below the terminal moraine of 1887, or about 1,400 feet from the nose of the ice in 1904, there occurs a moraine of the same general type as that described under this head in connection with the Victoria. This consists of very massive blocks of quartzite, arranged in a north to south ridge across the valley, having a breadth of about 400 feet and a height above the general valley floor of 20 to 40 feet. The largest block observed was measured by Messrs. Moseley and Todd and its dimensions, above ground, were found to be about 107.5 by 28 by 11 feet, from which it was estimated to weigh about 2,000 tons. A portion of this ridge is seen in plate XXXVI, figure 1, taken from one of the blocks of the moraine itself, looking toward the glacier up the valley. The blocks are blackened with lichens, more or less moss-covered, and carry enough soil to support considerable vegetation of a larger size. A spruce growing upon the moraine had been cut and with a circumference of 128 centimeters gave 243 rings of growth. A hemlock, also upon the moraine, with a circumference of 320 centimeters (50 centimeters from the base), was calculated to be 447 years of age. This estimate was based upon the average breadth of the annual rings of growth measured in the Illecillewaet and adjoining Asulkan valleys. This average breadth was found to be 1.140 millimeters, as compared with 0.884 millimeter in the Lake Louise Valley.

From the outer edge of this moraine, 1,500 feet down the valley measured along the stream, there begins another similar but larger moraine of the same type. Starting from the spur of Glacier Crest which separates the Illecillewaet and Asulkan valleys, the ridge swings out across the valley bearing N. 8° W., and then swings around to N. 15° W. It is 200 to 300 feet across and some 50 to 60 feet above the valley floor, somewhat steeper toward the glacier. The blocks are very coarse quartzites and schists, blackened with lichens, and presenting angular outlines. The largest block noted was estimated to weigh 1,250 tons. The usual filling of a moraine, gravel, sand, and clay, is practically absent. Upon the eastern side, for a portion of its length, it is covered by a mass of broken tree trunks which were swept from the side of Mt. Eagle by an avalanche (plate XXXVII, figure 1) some decades ago. Enough soil has accumulated about the rocks

FIG. 1.—"Bear-den moraine" made conjointly by the Illecillewaet and Asulkan Glaciers. Strewn with timber avalanched from the right-hand mountain slope.

FIG. 2.—Illecillewaet Glacier in 1897. Photographed by Notman & Son, Montreal. Compare with plate XXXVI.



Map of Asulkan Glacier, Asulkan Valley, Selkirk System. Surveyed and drawn by W. H. Sherzer, August, 1904 Field assistants De Forrest Ross and Frederick Larmour. Elevations from A. O. Wheeler.

to support a growth of raspberries, blueberries, etc., and also a few spruce 8 to 12 inches in diameter. The bulk of the material lies to the west of the glacial brook and was derived from the eastern side of Glacier Crest and Mt. Lookout, the cliffs of which have a northwest-southeast trend. The shape of the moraine and the way in which the blocks have been deposited indicate, as noted by Prof. Penck at the time of his visit, that the moraine was built conjointly by the former Illecillewaet and Asulkan glaciers. The blocks contributed by the Asulkan came from the western side of Glacier Crest and the Asulkan Ridge, and are much less in amount than those derived from the eastern side and transported by the Illecillewaet. The largest tree found growing inside of this moraine was calculated to have been 520 years old when it died and from the condition of its wood and bark to have been dead about 30 years.

CHAPTER VII.

ASULKAN GLACIER.

1. General Characteristics.

Lying at the head of the Asulkan Valley, upon the opposite side of Glacier Crest from the Illecillewaet Glacier (see plates XXXII and XXXIII), is located the Asulkan Glacier. Its broad expanse of snowfield extends in a semicircle from Asulkan Ridge, past Leda, Pollux, and Castor to the northern extremity of the Dome, faces to the northward, and under the sunlight is of dazzling whiteness. The name is of Cree Indian origin and is generally said to mean "goat," but I am assured that it really means "bridge." The nose of the glacier lies about three miles from the station, reached by a picturesque and easy trail, except in the upper part, where the trail becomes steep. The glacier itself may be safely visited and studied without a guide, but no one should venture upon the névé unattended, as it is very treacherously crevassed. This glacier is the smallest and the most southern and western of the series here reported upon, its nose lying in longitude 117° 28′, west and latitude 51° 13′, north.

The glacier consists of three streams, two of which are closely united and the third separated from the other two except in the névé region where they are all united. The length of this third stream, measured from the Asulkan Pass, is about two miles, of which the first mile is névé and the lower mile is ordinarily free from snow during the summer season (plate XXXIX, figure 1). The breadth of the dissipator is about 1,800 feet in the upper part, but about the middle of its course it makes an abrupt bend from the north to the northeast and tapers gradually to a sharp nose. The eastern margin curves around gradually to the nose, while the western side is curiously straight, cutting diagonally across what appears to be the natural course of the glacier. There seems no apparent reason for this abrupt bend in the glacier and for the remarkably straight western margin of the ice, but the explanation will appear in what follows. This peculiar contouring of this stream gives it the general form of a bear's paw—a *polar* bear

—in which the straight margin represents the sole. From near the heel of this foot there extends southward a long, slender ridge of glaciated rock, carrying more or less morainic matter, which separates this eastern ice stream from the double ice mass immediately to the west (plate XXXIX, figure 1). Judging from the line of crevasses and faulting across the névé, there lies another similar ridge, parallel with the first and about one-quarter mile to one-half mile to the west, which separates this mass into two streams, each having its own separate nose, as shown upon the map. This ridge is apparently the continuation of the line of bedrock exposed along the right-hand margin of the westernmost ice stream. The névé line upon this glacier is about 7,000 feet above sea-level and the main portion of the névé lies between this altitude and 8,000 feet. From the Asulkan Pass (7,710 feet) to the nose of the easternmost stream the descent is 2,110 feet, or at the rate of 1,055 feet to the mile. The altitude of the nose is 5,600 feet, or some 800 feet higher than that of the Illecillewaet, due apparently to the smaller volume of ice in the Asulkan and its dissipation at three separate points. The altitudes of the two higher noses to the west are about 6,000 feet, or the same as the Victoria. So far as may be judged from the crevasses and faultings, the ice responds fully to the irregularities in its bed which indicates that it is relatively thin. The surface slope of the western and middle streams is very steep; that of the easternmost, or main, stream is much more gentle, amounting in places to not more than 6°. Toward the nose the inclination becomes 25° and then drops off to but a few degrees, so that it may be readily ascended. Upon either side of the stream the marginal slopes are steep for a few hundred feet back from the nose.

2. Piedmont Characteristics.

If the reader has covered Chapter IV of this report he will have recognized already the piedmont character of the Asulkan, which consists of three commensal streams. The glacier is of peculiar interest because it is an illustration of a piedmont glacier in its senile condition. It has reached its second childhood and now illustrates the disintegration of a piedmont glacier into the component streams, the union of which in its youth gave rise to the glacier itself. Every glacier of this type begins with the independent development of a system of Alpine glaciers, coördinate in importance, which coalesce laterally into a single ice mass. The length of the glacier is determined by the length of the separate streams composing it and its breadth by the number of streams and their combined breadth. In the final stages of dissolution, which must come sooner or later in its life history, the piedmont glacier shrivels back into the original Alpine components. The eastern tributary has already separated sufficiently so that it may be regarded as an independent glacier. The other two have separated for a distance of about one-fourth of a mile, but the separation will not be complete until the ridge of rock above noted has appeared at the surface of the ice. The middle stream covered the ridge of rock, now exposed between it and the eastern stream, and sent its nose down the valley as far as the drainage brook

FIG. 1.—General view of Asulkan Glacier in 1902. Copyrighted, 1902, by the Detroit Photographic Co.

FIG. 2.—The Asulkan glaciers and snowfields from Avalanche Mt. (elevation 9,387 feet), showing a decadent piedmont glacier. Photographed in 1901 by Arthur O. Wheeler.

shown upon the map. There it formed a series of terminal moraines upon its eastern side, the eastern component standing at about the same level and forming a similar series. The sudden bend noted in the eastern component, one-half mile back from the nose, resulted from its pressure against the side of the middle stream which it was unable to force aside. Conjointly they formed a straight medial moraine from the bend to the nose. Upon the more rapid retreat of the middle stream and its disappearance from this part of its bed, this moraine became the left lateral of the easternmost stream (plate XXXIX, figure 1), and was of such a massive character that it has continued to deflect the ice from its natural course.

In plate XXXIX, figure 1, we have shown nearly the entire eastern and middle streams of the Asulkan, and a portion of the névé of the western. A distant view of the entire glacier is given in plate XXXIX, figure 2, taken by Wheeler from the summit of Avalanche Peak (9,387 feet) in 1901. The Dome may be recognized from its contour and from it there is seen to be a broad ridge extending valleyward and marking the western limit of the present Asulkan Glacier. To the right of this ridge, along the eastern slopes of Mts. Afton (8,423 feet) and Abbott (7,710 feet), four marked depressions occur, each containing small-sized glaciers. The contour of the rocky slopes separating these amphitheaters, or *cirques*, as they are termed, proves that at an earlier stage of glaciation these streams coalesced laterally and united with the present Asulkan, forming a grand, hanging, piedmont glacier, extending from the Asulkan Ridge to Mt. Abbott with at least nine or ten main commensals. Previous to this stage they had united with others from the head and opposite side of the valley into a grand Alpine glacier, which became a tributary of the ancient Illecillewaet trunk glacier in Pleistocene time.

3. Nourishment.

The névé field of the present Asulkan is arranged in the form of a semicircular belt, extending from the Asulkan Ridge upon the east around to the Dome upon the west, having a length of about three and a half miles and an average breadth of perhaps three-fourths of a mile. The area of this field is somewhere between two and a half and three square miles, or less than half that of the Illecillewaet névé field. The amount of precipitation over this field cannot be essentially different from that given for the neighboring glacier (page 82). From an elevation of about 7,000 feet the névé snows reach up to the crests of the bounding ridges, in many places, attaining an elevation of 9,000 feet. It is possible to pick out, in a general way, the névé fields by which the separate ice streams are nourished. The eastern stream receives its supply from Asulkan Ridge (9,100 feet) and from the Pass (7,710 feet), the former moving westward down the oblique slope and delivering its supply of ice and subglacial débris to the right side of the main stream flowing from the Pass. A still less amount is received from the opposite side from the snow that accumulates upon the northern slope of the unnamed peak (8,700 feet +) lying to the east of Leda. The Pass and upper névé are reached by means of the right lateral moraine. Judging from the course of the transverse

crevasses, which lie at right angles to the main direction of flow, the névé that accumulates between this minor peak and Leda (9,133 feet) moves northward and nourishes the middle ice stream. The oblique course is taken probably because of the continuation southward of the ridge of rock previously noted as separating the middle and eastern streams. The presence of a similar ridge beneath the ice deflects the névé snow and ice from the northern slopes of Castor (9,108 feet) and Pollux (9,176 feet), to which is added that from the Dome (9,029 feet), and thus is obtained the supply for the double-nosed western ice stream. The middle stream is least well supplied at the present time with ice from the névé field and has receded farthest. It seems very probable that when the ice was thicker over the névé there was relatively less of it deflected to the western stream by the subglacial ridge and this fact permitted the middle stream to maintain the same length as the now better nourished eastern. The superficial layers from Castor and Pollux could move directly across those which the configuration of the bed deflected northward, but as the general elevation of the névé was lowered a relatively greater and greater percentage of ice was deflected to the western stream and the nose of the middle stream retreated steadily some 2,200 feet up the slope, to an elevation at present 400 feet higher than the nose of the eastern stream. Were the ice of all three streams now concentrated into a single one it is probable that the nose would attain as low an altitude as that of the Illecillewaet.

4. Moraines.

Owing to the absence of high, overtowering cliffs, such as we find in the case of the Wenkchemna and Victoria glaciers, the névé fields of the Asulkan receive very little rock débris over their surfaces. In consequence, the ice itself, except along the margins, is quite free from rock fragments. As in the case of the neighboring Illecillewaet collecting basin, conditions are favorable for receiving wind-blown dust from peaks and ridges towering above the snow. This dust is distributed somewhat evenly over the snow and, when concentrated by melting, gives rise to the stratification and imparts a soiled appearance to the ice about the lower margins.

The right lateral moraine of the eastern ice stream makes its appearance just east of the nose and south of the stream from Asulkan Ridge. It rises at once into a conspicuous, sharp-crested ridge, extending south-southwestward, and bending abruptly to the south-southeast, attaining the length of a mile before it dips under the névé snow. The lower portion of the moraine seems entirely free from ice, the outer slope carrying fir and spruce 50 to 60 years of age. The inner slope is more steep and has younger vegetation, indicating that the ice has within a few decades withdrawn from the moraine. The crest rises to a height of 60 to 70 feet above the valley floor upon which the glacier rests. The rocks consist largely of bruised and rounded quartzites and schists, which in the upper part are embedded in a matrix of glacial clay. This material appears to come from beneath the glacier that covers the western slope of Asulkan Ridge,

FIG. 1.—Left Asulkan moraine shedding its rocky covering and exposing the ice core.

FIG. 2.—Débris-covered nose of Asulkan Glacier, August, 1904. Glacier had been advancing for some three or four years.

by which it is delivered to the main stream from the Pass, as previously noted, upon a level with its surface. This névé-covered glacier sustains the same relation to the Asulkan that the Collie and Gordon glaciers do to the Yoho. Between the crest of the moraine and the glacier there intervenes a steep boulder slope, about 300 feet broad in the lower portion near the nose, but narrowing gradually for a half-mile, when the moraine and ice meet. Opposite the nose, upon the eastern side there is an outcrop of a silvery schist, with its strata upon edge, which has been glaciated and plucked.

The development of the left lateral of the eastern stream from a former medial has already been described and its very straight course obliquely across the valley been accounted for. Originally, this moraine may have been largely subglacial, or englacial, the material being derived from the basal layers of the ice. The slope of the valley floor is northward, while this lower half-mile of the moraine bears northeastward. After making the very abrupt bend noted, the moraine continues for a quarter-mile farther, resting upon the rocky ridge of quartzite and a greenish schist. This ridge raises the base of the middle stream above the present surface of this portion of the eastern stream. The moraine consists very largely of ground moraine, supplied apparently in large part by the middle ice stream, but instead of clay the filling is a glacial sand. The finer material may have been removed by currents too gentle to transport this sand. The inner slope of the moraine is steep, the outer is more gentle down to the drainage brook from the middle nose. The crest of the moraine rises 125 to 150 feet above the floor of this valley. About one-quarter mile back from the nose this moraine begins to shed its cover of rock débris, revealing in a most interesting manner the real structure of such a moraine. From this point up the valley the moraine is a typical, sharp-crested structure (plate XXXIX, figure 1), but here the débris has begun to slip to either side, forming a double ridge with a continuous ice crest between. Plate XL, figure 1, gives a view of this exposed ice core, looking up the glacier along the inner side. The highest portion of the ice ridge attains a height of 25 to 30 feet, which is being rapidly acted upon by the sun in midsummer. Where it has been longest exposed the ice has melted below the general level of the glacier, forming a depression with a ridge of rock débris upon either side, the outermost one being quite prominent. Into the depression the material from either side has begun to roll and slide, thus protecting the ice at the bottom of the depression from the sun. Had the thickness of the ice proved sufficient, in time the rock débris would have gotten back, in large part, into the depression, allowing the ice to melt upon either side and starting again the formation of a single-crested, typical moraine. Thus it appears that moraines may, under certain circumstances, pass through the same series of stages as those described for surface lakelets upon page 57 of this report.

About the eastern nose there has been pushed up a ridge of ground moraine, from 12 to 15 feet high, into which the ice nose plunges and buries itself. Upon this ridge minor ridges, but a foot or two in height, also occur, as seen in plate XL, figure 2. At times the nose is so deeply buried that it is difficult to find it for pur-

poses of measurement. When the middle stream stood at this lower level, the two built a series of three or four latero-terminal moraines which curve gently down the valley from the lower ends of the laterals. The inner terminal of the middle stream has the appearance of age, compared with the others lying just east, and is being covered slowly with low shrubs and evergreens. From this difference in age one would infer that the ridges of the series, lying to the east, had been built by the eastern stream alone. The nose of the middle stream, especially upon its eastern side, rests largely upon bedrock, more or less strewn with rock fragments. The rock here, as elsewhere about the glacier, consists of quartzite and schist, plucked and glaciated. Along its left side, back as far as it has become separated from its neighbor, it has built a sharp-crested, lateral moraine, which in the lower half is double, curving gently down the bouldery slope. The inner slope is steep, the outer long and more gentle. The boulders are rounded and bruised but only occasionally well glaciated. The double western nose is similar to the middle, in that it is steep, perched high up on the slope, has bedrock exposed upon its eastern side, while upon the left it has built a short, sharp lateral extending up to the névé. In front of the western and middle streams there has been uncovered a steep slope of bouldery ground moraine so recently that trees have not been able yet to get anything more than a start.

5. Crevasses.

Owing to the irregularities in its bed, the steep slopes, and the apparent thinness of the ice, the Asulkan streams are badly crevassed and faulted. The névé fields of the western and middle streams cannot be traversed with any degree of safety, while that of the eastern calls for the greatest skill in locating the snow-covered death-traps (plate XLI). The crevasses in the névé portions are mainly of the transverse type, caused by the rapid movement of the ice over an irregular, steep slope. They stand approximately at right angles to the direction of motion and furnish a clue as to the general movement of various portions of the névé field. Just below the névé line the eastern stream encounters, in its central portion, an obstruction by which the ice is shattered in every direction, but mainly transversely (plate XXXIX, figure 1). The descent is not rapid enough to constitute a cascade and the blocks, at first angular, become sharpened by melting into seracs but retain their vertical position until melted away at the base of the slope. The development of these seracs is well shown in plate XLII, figure 1. The ice exposed portion, or dissipator, of this stream shows numerous marginal crevasses along either side of its course, those upon the eastern side, in the lower portion, extending beyond the central axis. Those upon the western side are not so strongly developed. It is upon the middle stream that the dirt band crevasses occur figured in connection with the discussion of this subject (plate XVII, figure 1). The slope, however, is too steep for their formation and preservation.

FIG. 1.—Stratification of Asulkan Glacier. The dates are added upon the supposition that the strata represent seasonal deposition. Copyrighted, 1902, by the Detroit Photographic Co.

FIG. 2.—General view of Asulkan Glacier in 1898. Reproduced through courtesy of the Messrs. Vaux. Compare with plate XXXIX, figure 1.

6. Ice Structure.

The névé-covered portion of the ice acquires a very perfect stratification as the result of wind distributed dust and periodic melting over the surface. This structure is beautifully shown in the crevasse walls and the faces of the numerous faults in the ice. In the photograph of the Detroit Publishing Co., reproduced in plate XLI, the successive layers, with the minor stratification seams, are clearly shown. The correspondence of the strata upon opposite sides of the crevasse shows that there had been no faulting. From his heel to the crown of his hat this guide pictured is about six feet in length and, by comparison, we ascertain that the strata shown range from three to twelve feet in thickness. The picture was taken during the summer of 1902, and in looking at the uppermost stratum it is forced upon one's belief that this represents the compacted snow that accumulated over this spot during the season of 1901–2. Part of this snow was precipitated directly, part of it may have been drifted by wind action. It may have lost some by wind action, as well, during the season of accumulation. It has been compacted by melting, pressure, and occasional rain into a fine granular ice. If we are right in supposing that this stratum represents the accumulation during the season of 1901–2, minus the loss by the combined agencies, then the stratum upon which it rests must have accumulated during the season of 1900–1. Passing down the side of the crevasse we may thus assign dates to the successive strata, finding that they reach back to the season of 1895–6. It is especially interesting to note that the deposits supposed to have been laid down between the summer of 1898 and that of 1902 average considerably thicker than those between the summers of 1895 and 1898, since this dividing date falls very near the supposed date of the beginning of the phase of increased precipitation in this region. It is further to be noted that the stratum marked 1898–9 is the thickest of the series. It is very unfortunate that our precipitation data are not fuller for the locality. In order to serve the present purpose in establishing a relationship between the amount of precipitation and the thickness of the strata in the névé, a combination should be made of the last three months of the year with the first nine of the following year. This would unite practically all of the snowfall and the rain and melting water of the following summer, as it is combined in the stratum itself. In a paper upon the Canadian Pacific Railway, from Laggan to Revelstoke,[1] Mr. William Vaux gives the average snowfall for Glacier House from 1895 to 1898 as 31 feet, based upon records kept by the station agent, this being but 83 per cent. of the normal. From October, 1898, to May, 1899, inclusive, the snowfall alone amounted to 43 feet 8½ inches, being 17 per cent. above the normal. The records are lacking up to 1902, for which year the Meteorological Service reports 13.88 inches of rain and 347 inches of snow, or a total equivalent of 40½ feet in snow, or 14 per cent. below the normal. By referring to plate XLI it will be seen that the stratum assigned to the year 1898–1899 is the heaviest of the series while that for 1901–1902 is light. From 1895 to 1898 the strata are

[1] *Proceedings* of the Engineers' Club of Philadelphia, vol. XVII, 1900, p. 73.

thin, corresponding to the average lighter snowfall above reported for these years.

A still further confirmation of the conclusion reached above, that from the middle of the year 1898 there has been a marked increase in the snowfall, is furnished by the notes and photographs of the Messrs. Vaux, to be noted later. Their photograph of 1898 shows a large amount of rock exposed along the slopes of Leda, Pollux, and Castor, as well as between the eastern and middle ice streams. In 1899 they note that the névé line is lower and the *hanging glaciers* are much more active, giving rise to frequent avalanches, which were very infrequent in 1898. When their photograph of 1898, reproduced here as plate XLI, figure 2, is compared with that of the Detroit Publishing Co., taken in 1902 (plate XXXIX, figure 1), the increase in the amount of névé is striking, the presence of the bergschrunds, in areas that were bare rock, indicating that glaciers had formed in the meantime and that there is not simply a covering of loose snow, such as might fall in a night. In looking over the broad snow expanse one does not think of there being *hanging* glaciers upon the slopes of Castor and Pollux, as they seem to blend with and be an integral part of the general névé field. In 1898 they were separated sufficiently so that it was natural to think of them as being detached. In two weeks of August, camping in plain sight of the region, in 1904 and 1905, the writer does not remember to have seen or heard a single avalanche from this quarter. They were frequent in the summer of 1899, and, presumably, continued so until the space between the lower névé and the upper became so filled in as to prevent further slides. From all the evidence obtainable it seems most probable that the major stratification planes in the Asulkan névé represent the breaks between the successive year's snowfall, and that a phase of deficient precipitation closed in this region about the middle of the year 1898, since which time the average annual precipitation has been in excess of the normal.

The disturbance of the ice noted upon the eastern stream does not destroy the stratification, since it extends only part way across the stream and is not intense. The strata are, however, more or less tilted and distorted. The lower stratum is wedge-shaped, having apparently lost from its basal portion by subglacial melting. The blue bands in this stratum are not parallel with its upper surface, but cut it at angles of about 13° to 14°, being more nearly parallel with the valley floor. In the stratum just above, the blue bands and stratification planes were conformable. In general, the blue bands were found to be regularly developed, quite in contrast with the stratification. The dirt stripes showed well over the surface and margins of the eastern stream, some excessively thin ones being observed and previously noted (page 54). About the nose, upon the walls of some of the longitudinal crevasses, the blue bands were found to dip back into the glacier at angles of 11° to 28°. About the eastern side they were found to dip downwards and inwards, nine observations giving an average of 46°, with a range from 36° to 57°. The granules about the nose are small, compared with those seen in the larger glaciers, and will average less than a half-inch in diameter.

7. Drainage.

Owing to the crevassed condition of the ice the surface streams are small, dropping into the glacier, or to the bottom, before they can develop any size. Over the névé area the water resulting from melting, or from rains, is at once absorbed. Over the ice exposed portions, during hours of melting, small rills and surface brooks come into existence, carrying water with a temperature of 32°. No lakelets were noted upon the glaciers, or about the margins, but upon the col, lying between Castor and the Dome, Mr. Wheeler found a lakelet of sapphire blue water. Under ordinary conditions there is practically no marginal drainage. In 1904, back some 800 feet from the nose of the eastern ice stream, a small flow was visible for a short distance. From each of the three noses there issue two to three drainage brooks, those from the eastern uniting with one another and with the drainage from Asulkan Ridge, after which is received the central flow from the middle portion of the glacier. That from the western commensal, along with the drainage from the hanging glaciers lying farther to the west, cascades into the Asulkan Valley, forming the "Seven Waterfalls." The flow from the eastern nose is the strongest and carries the most sediment, considerably more than the Illecillewaet. It fluctuates in volume during the day, reaching its maximum in the late afternoon, or evening, and being lowest in the early morning. The combined drainage from the middle and eastern portions of the glacier, along with that received from the Asulkan Ridge to the eastward, has cut a gorge 30 to 40 feet deep through the soft schist. This has the appearance of having been done since the withdrawal of the ice, but it may have been started by a subglacial stream. Under high velocity and charged with sharp, glacial sediment the cutting power of water must be rapid upon a soft schist. Its action upon quartzite boulders is well seen in the bed of the brook from Asulkan Ridge.

During the last week in August in 1904 and 1905, the average of 28 observations upon the temperature of the water from the eastern nose was 32.42° F., the range being from 32.0° to 33.0°. Two observations upon the water from the middle nose, upon leaving the ice, averaged 33.0°, while from the third nose it was 32.8°. Before receiving the middle drainage the temperature of the brook was 36.9° and after the two had united just above the schist cut the temperature was 37.8°. Passing down the valley some two miles, and receiving drainage from either slope, the temperature at the bridge across the Asulkan Creek averaged 42.6°. The water is here turbid but assuming more or less of a greenish cast. The stream from the Asulkan Ridge before receiving the flow from the glacier was found to average 36.5° (20 observations). These observations seemed to indicate that the maximum temperature was attained between 11:00 A.M., and 1:00 P.M., and that as the volume of water increased as the day advanced the temperature gradually fell. This is brought out in the table here given.

TEMPERATURES OF STREAM FROM ASULKAN RIDGE.

1904.			1905.		
Aug. 30.	7:10 A.M.	35.2°	Aug. 28.	6:00 A.M.	35.8°
Aug. 26.	7:15 A.M.	35.6°	Aug. 28.	7:00 A.M.	36.1°
Aug. 27.	9:10 A.M.	36.9°	Aug. 29.	9:00 A.M.	37.0°
Aug. 31.	10:15 A.M.	36.3°	Aug. 27.	11:00 A.M.	38.7°
Aug. 27.	1:10 P.M.	37.8°	Aug. 27.	2:00 P.M.	37.9°
Aug. 25.	6:05 P.M.	36.5°	Aug. 27.	3:10 P.M.	37.4°
Aug. 28.	6:15 P.M.	35.6°	Aug. 27.	4:00 P.M.	37.0°
Aug. 25.	6:50 P.M.	35.2°	Aug. 27.	5:00 P.M.	36.7°
			Aug. 27.	6:00 P.M.	36.3°
			Aug. 27.	7:00 P.M.	36.0°
			Aug. 27.	8:00 P.M.	36.0°

8. Frontal Changes.

Points of reference for the study of the frontal behavior of the lower Asulkan nose were established August 12, 1899, by the Messrs. Vaux and observations and photographs have been repeatedly made by them since. At that time they made an unsuccessful search for reference blocks previously marked by H. W. Topham. One year previously (August 23, 1898) they had visited the glacier and obtained a photograph from their "test rock," which was published, along with a brief description of the glacier, in the paper previously referred to.[1] A comparison of their test picture of 1898 (plate XLI, figure 2) with that of 1899 showed a slight shrinkage in the height and a slight increase in the breadth, "while the position of the tongue had not changed to an appreciable extent." The ice fall appeared to be less and they note that the névé line was lower, the glaciers upon the slopes of Castor and Pollux more active, giving rise to a number of avalanches, which seemed very infrequent in 1898. In marking the position of the tongue at the time of their visit in 1899 three rocks were selected in a line with the nose, the magnetic bearing of which was N. 85°35′ E. One rock was located upon the small, left lateral moraine, a second just below and to the right of the nose, while the third lay upon the inner side of the higher right lateral. In 1900 the Messrs. Vaux observed a retreat of 24 feet and "a marked shrinkage in every dimension." From 1900 to 1901 these observers reported an advance of 4 feet and for the two years 1901 to 1903 an additional advance of 36 feet.[2]

This glacier was first visited by the writer September 17, 1903, at which time it was found that the nose of the glacier lay 13½ feet beyond the Vaux line, which was readily located by the two well marked end rocks. This would indicate that the nose had retreated 2½ feet between the date of Vaux's measurement in 1903 and September 17 of the same year. The stone that had been marked near the nose had been pushed forward some 14 to 15 feet, turned on end and was about to topple over. Upon August 27, 1904, the nose lay 12½ feet beyond the line, indicating practically no change, when allowance is made for difference in

[1] "Some Observations on the Illecellewaet and Asulkan Glaciers of British Columbia," *Proceedings of the Acad. of Sci. of Phil.*, 1899, p. 121.

[2] "Variations of Glaciers," H. F. Reid, *Jour. of Geol.*, vol. XIII, 1905, p. 316.

dates of observation. Exactly one year later (August 27, 1905) the nose had made a retreat of 34 feet from the position held in 1904, standing now 21½ feet back from the reference line established in 1899. The nose consisted at this time of a thin slab of ice, sloping to the west and coated with fine débris. A relatively small amount of melting would cause a further recession of 30 to 35 feet. The ice in the left lateral moraine was found to extend four feet beyond the reference line and 25½ feet beyond the nose. Owing to the rock cover it could not be ascertained how much farther the morainic ice core extended. The movements of this nose may be summarized as follows:

CHANGES IN THE NOSE OF THE ASULKAN GLACIER.

(Eastern Ice Stream.)

1898–1899.	"Practically no change."
1899–1900.	Recession of 24 feet.
1900–1901.	Advance of 4 feet.
1901–1903.	Average advance of 18 feet.
1903–1904.	Retreat of 1 foot.
1904–1905.	Retreat of 34 feet.
1905–1906.	No change.

9. FORMER ACTIVITY.

a. Development and decadence. At a much earlier stage, presumably in Pleistocene time, the combined snows of the Asulkan Valley united into a great Alpine glacier, the ancient Asulkan, which was a tributary of the ancient Illecillewaet, and this, in turn, a tributary of the great trunk glacier that flowed southward in the Columbia Valley, to the west of the Selkirks. With the diminution of snowfall, and possibly also an amelioration of the climate, the glaciers disappeared from the main valleys and withdrew into the tributary valleys and alongside the steep, higher slopes. An Alpine glacier occupied the Asulkan Valley from the Pass to where the valley joins the Illecillewaet, some four miles in length, which was in part nourished by a hanging, piedmont glacier extending from the Pass to Mt. Abbott. This glacier sustained, during this stage, the same relation to the Asulkan lying in the valley, that the hanging Victoria sustains to the lower ice stream. The effect of these great ice masses upon the valley floor and sides was similar to that already discussed for the Victoria and Yoho glaciers (pages 61 and 80).

b. Bear-den moraines. Just before the complete and final separation of the Asulkan from the Illecillewaet, the Asulkan became loaded with very coarse, angular rock fragments, and only a minimum of fine material. This was at the same time that the Illecillewaet was similarly laden and, conjointly, they deposited the massive bear-den moraine described upon page 96. The most of its material was deposited upon its right, showing that it must have been received from the western side of Glacier Crest and Mt. Lookout. The amount carried was notably less than that brought down by its neighbor lying to the east of the Crest. The ridges about the head of the valley and along the western side were largely under snow and ice and could supply no such débris. After this load

of rock had been deposited the Asulkan began to retreat, withdrawing a distance of 3,500 feet up the Asulkan Valley. The front now halted and there was built a moraine of the ordinary type across the valley, consisting of fine and coarse material, intermingled with but few coarse blocks. From this we conclude that the glacier was, at this time, carrying the ordinary kind of load. The retreat was resumed and in the meantime the glacier became a second time laden with coarse fragments of the adjoining cliffs. At a distance of about 1,000 feet from the previously formed moraine these blocks began to be deposited and were dropped over a distance of some 500 to 600 feet, not so concentrated or imposing as the outer bear-den moraine. For the next 1,500 feet these blocks were scattered along the valley, implying that the supply over the surface had not been sufcient to bring about a halt. The retreat continued towards the head of the valley and at a distance of 2,000 feet farther a halt occurred and a moraine of the ordinary type was again built, with the usual quota of fine and coarse material. From the time then that the Asulkan was about to separate from the Illecillewaet it became twice loaded with coarse, angular fragments of quartzite, building a moraine of the bear-den type. In the interval it carried material of the ordinary kind found upon and within the ice and built a moraine of the ordinary type. Subsequently to the formation of the second, straggling, bear-den moraine, it has been carrying and depositing the usual class of material. It differs from the Victoria in that the ancient moraine of the ordinary type was deposited between the two bear-den moraines instead of outside the two, as in the case of the latter.

c. Rate of retreat. The only possible data for any estimates upon the rate of retreat up the valley must be drawn from a study of the forest trees and no one realizes any more strongly than the writer how unreliable and misleading such data may be. However, we may obtain an approximate minimum estimate by this means, which may have some interest, if not real value. Some exceptionally large spruces and hemlocks are found near the mouth of the valley and within the outer bear-den moraine. Based upon the average thickness of the rings of growth, noted upon page 96, two of the largest seen should be 525 and 598 years of age, respectively. Toward the schist cut, at the head of the valley, the rings of growth become coarser and the trees smaller, the difference in elevation amounting to about 900 feet. One of the largest firs showed 161 rings of growth and a still larger hemlock growing near was estimated to have lived about 250 years. Assuming that it required about the same length of time for the trees to get started at either end of the valley, it took the Asulkan about 350 years to retreat the two miles from the mouth of the valley to the schist cut, or at the average rate of about 30 feet a year. From the schist cut to the present nose, about one-quarter mile, the valley opens and the retreat must have been much slower, owing to the volume of ice to be melted away. If we assume that it required 50 years for the hemlock noted to get started, the minimum time involved would be 300 years and the maximum average rate of retreat for this part of the glacier would have been about 4.4 feet per annum. If the cut in the schist

FIG. 1.—Development of ice seracs from glacial blocks, Asulkan Glacier, August, 1904.

FIG. 2.—Disrupted quartzite blocks, near head of Paradise Valley, Canadian Rockies. Illustrating plucking power of glaciers.

has been made entirely since the withdrawal of the ice from that part of the valley, then the rate of cutting would be over an inch a year, which is probably too fast for even water at high velocity, charged with glacial sediment and operating upon rather soft rock. This seems especially true when we consider that the supply of water is much reduced, or possibly entirely shut off during the greater part of the year. It is very probable, however, that the narrow gorge may have been largely formed subglacially, while the glacier extended far down the valley. Schist layers upon edge do not well record ice action, but even if such evidence of glaciation was present it may have been destroyed by subsequent weathering. It must be noted that the time of retreat determined as above would represent only a minimum value and the rate of movement per annum for a definite distance would represent a maximum.

CHAPTER VIII.

SUMMARY AND CONCLUSIONS.

In the closing chapter it is desired to give a concise statement of the most important results secured in the two seasons' work and the conclusions reached. The writer desires further to express for the benefit of those who may be interested his conviction concerning some of the theoretic questions that have arisen in connection with the study of these Canadian glaciers.

1. Physiographic Changes in the Region.

a. Mesozoic peneplain. From the close of the Archæan to the end of the Laramie, conditions were very favorable for the accumulation of sedimentary deposits in the region now covered by the Canadian Rockies and Selkirks. Strata belonging to the Palæozoic and Mesozoic eras of the world's history reached the extraordinary thickness, according to the work of Dawson and McConnell, of 50,000 to 60,000 feet. Much of this was brought above sea-level during the Mesozoic era and further sedimentation ceased except in certain restricted regions in the eastern part of the area, where conditions were still favorable for marine or fresh-water accumulations. During countless ages of exposure to the manifold atmospheric agencies there was developed a broad Mesozoic peneplain, extending in a direction to the west of north and sloping eastward and westward, determining the general direction of flow of the drainage streams. It was during this stage, probably, that the mountains suffered their greatest denudation, rather than since. The great Laramide revolution of the western United States and Canada completed the formation of these mountains, the pressure coming from the west in the region under consideration, and producing a series of parallel folds and troughs, with numerous overthrust faults, all having a north-northwest to south-southeast trend. The upheaval was slow enough so that many of the original drainage streams were able to maintain their general direction of flow, cutting their way continuously

across the gradually rising ridges of the mountains and the lesser folds of the foot-hills. In many cases, the troughs, lying between parallel ridges, or the gaping crevasses in the rock strata parallel with them, captured the drainage and a system of longitudinal river courses was developed, much younger than the transverse system. As a result of these great orogenic movements, combined with the atmospheric and aqueous agencies operating since, we have an uplifted and dissected peneplain.

b. Pre-pleistocene erosion. With the completion of the mountains at the close of the Mesozoic, the more or less sluggish streams of the ancient peneplain acquired velocity and renewed their activity, cutting deeply into their former beds. The newly born longitudinal streams incised still further the channels provided for them and there were developed two systems of V-shaped valleys more or less intimately connected. The agencies of weathering broadened the valleys above and delivered the rock fragments to the stream below, by which tools the water still further deepened its beds. This action went along slowly from the beginning of Cenozoic time to the beginning of the Pleistocene, during which time the roughly angular blocks were carved into jagged peaks and many of the divides into sharp-crested ridges. The outline of the old peneplain is to be recognized only when one ascends until his eye is on a level with its uplifted surface, when peaks and ridges all blend into the common level that cuts the sky at the limit of vision. See plates II, XVI, and XXXII.

c. Pleistocene erosion. The opening of the Pleistocene and the advent of the glaciers introduced a new geological agent into the region. A reduction in the mean annual temperature, combined with an increase in precipitation, allowed the snow to accumulate about the higher peaks and ridges more rapidly than it could melt away during the warmer season. Year after year the snow banks thickened, sent their avalanches into the valleys faster than they could melt away, and thus the mountains became enveloped in snow and ice. Glaciers moved down from the more elevated valleys, joined forces with their neighbors, grew in volume and power, took possession of the river valleys, and sent massive tongues of ice far beyond the limits of the mountains. The valleys were filled to depths of 4,000 feet from their floors, in certain cases, the actual elevation rarely falling below 7,000 feet above sea-level. These ice streams exercised a powerful effect upon the rock strata over which they passed; in general, rounding and smoothing their outlines, cutting down prominences, and truncating mountain spurs. In some cases where plucking was most active the rocks were made still more jagged and irregular than the ice had found them. The lower half of the valleys, which had been invaded by the ice, had their floors broadened and their sides correspondingly steepened, giving this portion of the valley a U-shaped cross-section. The upper portion, under less pressure of ice, still retains more or less of its pre-pleistocene V-shaped form, the sides being simply smoothed and fluted. The extension of these V-slopes until they intersect in the valley may be assumed to mark the level, approximately, from which the glaciers began deepening their beds. In the floors of the valleys at certain places rock-basins

were gouged out, either because of the structure or softness of the rock or because of the more vigorous ice action for a limited distance. At the heads of the separate valleys, broad semicircular amphitheaters, or cirques, were cut out, an interesting series of which is shown in plate XXXIX, figure 2, at the right side of the view.

From observations made upon the plucking power of glaciers in the various valleys, the writer is quite prepared to admit the sufficiency of glaciers as engines of erosion, especially where the ice is very thick, concentrated in its action, and operates for long time over stratified, or much jointed formations. In addition to the plucked mountain peaks observed in the Yoho Valley (page 79), there is to be seen in Paradise Valley, lying between Lake Louise and Moraine Lake, a very striking case of plucking, in which very heavily bedded quartzite has been bodily removed. The upper stratum is 10 to 12 feet thick, and about the margin of the stratum, the upper surface of which is very perfectly glaciated, immense blocks, some of them as large as small houses, have been started a short distance and then left. Apparently in the waning stages of the glacier the ice had been unable to get hold of blocks which it had been able to pry loose from the parent bed. This occurs near the head of the valley and it is difficult to resist the conclusion that hundreds of feet of similar, or less resistant rock may have been removed between this ledge and the mouth of the valley. Glaciers with their basal layers shod with hard rock débris would be able to erode slowly. The amount of erosion accomplished in this way would depend simply upon the time, but it has probably always been small, when compared with that due to plucking. It seems likely that pure ice can have only an insignificant effect upon ordinary rock, when simply pushed across it. The greater the pressure the more the melting, and unless disruption of the rocks occurs, the only effect would be to give the rock a polish.

d. Pleistocene deposition. During the maximum stages of glaciation there were so few overtowering cliffs above the névé fields and the ice streams themselves that very little supra- and englacial material was carried. In consequence during the stages of halt, that must have succeeded one another in the retreat from the outermost position attained by the trunk streams, no great, conspicuous moraines were formed. Not until the glaciers had retreated to near the heads of the valleys do we find prominent terminal moraines. At this stage the level of the ice and snow has dropped below the cliffs so that it is possible for the glaciers to acquire, in many cases, a heavy load of rock débris upon their upper surfaces. Glaciers like the Yoho have still been unable to build prominent moraines from materials carried supraglacially. The detritus resulting from the destruction of rock strata in the valleys and over the rocky slopes was carried near the bases of the glaciers, or pushed and rolled along between the ice and its bed. This resulted in the making of much ground moraine, much of which remained in the valleys in places favorable for its lodgment. During the maximum stages of glacial development much of this subglacial material was carried beyond the mountains and deposited as till, or it found its way into the

rapid streams, where it was immediately assorted into boulders, cobbles, gravel, sand, and clay. In these various forms it was built into the terraces, flood plains, deltas, etc., which characterize the drainage streams. The finer materials made their way to the Pacific and Hudson Bay. The argument against great glacial erosion that the material removed cannot be found, seems to the writer to carry little weight. If one looks far enough and is able to distinguish the Pleistocene and post-pleistocene deposits from the earlier, it seems probable that enough would be located to restore the mountains and valleys to the condition in which the glaciers found them. In the Bow and Cascade valleys, near Banff, Wilcox discovered two distinct till sheets, indicating that there were, at least, two main advances of ice through this section of the mountains. Eastward from the mountains McConnell and Dawson found three such sheets, derived either in whole or in part from the Rockies.

2. Precipitation.

a. Geographic distribution. Owing to the north to south trend of the four mountain systems that here constitute the great Cordillera, their limited breadth, their nearness to the warm waters of the Pacific, and the relation of the region to the great cyclonic areas that enter from the Pacific, conditions are favorable for an abundant precipitation upon the western slopes of the mountain systems. The arrangement of the four systems being such that they increase in height successively from the Coast Range to the Rockies, enables all of them to get a fair share of the available precipitation. The prevailing winds are from the west and laden with moisture. In ascending the windward slopes much of this moisture is precipitated as rain, or snow, owing to the expansion and consequent cooling of the air. In the condensation of this moisture its latent heat is liberated and raises the temperature of the air. In being drawn down the leeward slope by the general cyclonic movement of the atmosphere, the air is still further warmed by the compression to which it is subjected, its capacity for holding moisture is increased, and it reaches the same elevation upon the leeward slope much dryer and warmer than it was at the corresponding level upon the windward slope. This gives rise to the well-known "chinook wind," the equivalent of the Alpine foehn. The Selkirks, lying to the west of the Rockies, receive the heaviest precipitation, are more completely forested, experience more frequent avalanches of snow, and send their névés and glaciers to lower levels. The shifting of the centers of the cyclonic areas to the south of this region would give rise to prevailing easterly winds, which in the winter would be colder and dryer and in the summer warmer than those which now prevail, and, without doubt, bring about the disappearance of glaciers from this part of the mountains.

b. Climatic cycles. Precipitation records are too scanty and fragmentary for safe generalization concerning the occurrence in this region of oscillations known to occur in the other parts of the world. Still there are several lines of evidence which indicate that a phase of reduced precipitation closed in the Selkirks

and Rockies about the year 1897 or 1898, and that since then the average for the series of years is in excess of the normal. These lines of evidence consist (1) in the records kept by the station agent at Glacier House of the snowfall, and of the records of the Canadian Meteorological Service for Banff and Calgary. With the exception of Agassiz, which appears to be one of Brückner's "exceptional coast stations," the other records do not reach far enough back to be of service. (2) The notes and photographs of the Messrs. Vaux in the Asulkan Valley, made in 1898 and 1899, when contrasted with those of later date, indicate the close of a series of years with 1897-8, during which the snowfall was much less than since. (3) The thickness of the strata in the névé of the Asulkan Glacier, assuming that they represent annual accumulations, indicates at the point photographed in 1902 that three years of diminished precipitation closed with 1897-8 and were followed by four years during which the average precipitation was in excess. (4) In 1883 and 1884 Dawson found over a belt of country 140 miles long in the western part of the Rocky System, evidence of a recent high-water stage of the lakes, which resulted in the killing of trees that must have grown during a prolonged low-water stage that preceded. The condition of the trees indicated that they had "been killed within a few years." If we assume that the wet phase that gave rise to this condition of the lakes closed about the year 1880, then we should expect the inauguration of another wet phase about the years 1897 or 1898. Finally (5), from the photographs that have been made of the Illecillewaet Glacier we have proof of the long-time oscillations of the level of the ice about the névé line, giving rise to

c. Ice waves. When photographs taken from the identical view-point in 1888, 1897, and 1905 (plates XXXVI and XXXVII) are compared, they show a marked fluctuation in the height of the ice along the sky-line. The ice appears to have been at a minimum about 1888 and to have been approaching the same condition in 1905, possibly attaining it during the current season of 1906. The crest of a wave, or impulse of ice from the névé appears to have reached the sky-line about 1897 to 1899. The time from trough to crest would represent a quarter of the period, that from trough to trough, half of the period of the complete oscillation of the ice wave. In this case our data would indicate a period of 36 to 40 years, agreeing well with the precipitation cycles to which these ice waves are to be ascribed. It has been shown by the work of Finsterwalder, Blümcke, and Hess that the advance of a glacier is due to the progress of an ice wave along its length, moving more rapidly than the ice itself. The Illecillewaet in 1887 was experiencing about its nose the last stages in the effect of the arrival of such a wave. The trough, then at the sky-line, moved valleyward and permitted the retreat of the nose of the glacier, which retreat was probably at its maximum about the year 1895 or 6, or some 8 or 9 years after the start. The data for 1902 to 1905 seemed to indicate that an advance was about to be inaugurated but the very marked retreat of 1905-6 shows that this advance has been somewhat delayed. When later the year is known at which date the advance was most rapid we may figure the rate at which the wave travelled the

length of the glacier. It is a matter of much interest to try to connect the crests and troughs of these ice waves with the corresponding wet and dry phases of the precipitation cycles noted above. Since the crest of the wave arrived at the sky-line in 1897–9, just at the close of the dry phase and the beginning of a damp one, the wave must be referred back to the damp phase of the preceding climatic cycle, closing in the late 70's, or early 80's, so far as we may judge from the observations of Dawson upon the level of the lakes in the western Rockies. This would give the "reservoir lag" of one-quarter of the period, required by Reid's calculations, and an additional 16 or 18 years for the impulse to reach the crest of the rim. The trough resulting from the dry phase closing in 1897 appears to have moved out from the reservoir more promptly, possibly owing to certain local conditions.

3. Piedmont Type of Glaciers.

Three representatives of this unusual type of glacier were found, two of which, the Wenkchemna and Asulkan, are here described; the third is the Horseshoe Glacier at the head of Paradise Valley, in the Rockies. This type of glacier is always compound, being made up of a series of glaciers of the common Alpine type, all of coördinate importance, which coalesce laterally but retain their individuality from névé to nose. Since none of them are *tributary* to any of the others, but independent in all essential respects, they are here referred to as *commensal* streams, in order to indicate this relationship. These separate streams have temporarily united forces and found strength in the union. In the case of the Wenkchemna it is very probable that very few, if any, of the commensals could exist separately. In its earliest stage of development the piedmont glacier begins as a series of Alpine glaciers, either with or without tributaries, lying in neighboring valleys. With the increase in precipitation the level of the surface of the separate streams rises until they cover the divides between adjacent streams, or the, at first, separate Alpine glaciers reach out upon the *pied-mont* and there coalesce laterally. In its senile condition, a stage to be reached sooner or later, the piedmont glacier returns to its condition of youth and disintegrates into its component streams, as illustrated by the Asulkan of to-day. In the case of the Horseshoe Glacier some sixteen different commensal streams may be recognized, the most western four or five of which have almost completely separated from the others. The glacier has a meager snow-field, the supply for which is avalanched from the slopes of Mts. Ringrose (No. 10), Hungabee, Lefroy, and the southern side of the Mitre. Observations upon the Wenkchemna showed that each separate nose may have its own independent behavior and that the movements of the glacier as a whole cannot be known unless data are collected for each component stream.

4. Parasitic Glacier.

From the hanging glacier upon the eastern shoulder of Mt. Lefroy there is avalanched to the back of the Mitre Glacier quantities of snow and ice, falling

a vertical distance of some 2,000 feet and accumulating along the base of the cliff. The ice of the glacier is broken into fragments, some of it disintegrating into its component granules and much of it ground into ice dust, destroying completely the stratification and lamination of the hanging glacier. The avalanches occur mainly during the late spring, summer, and early fall, and as a result of the spreading of the fragments from sliding and rolling there is made each season a stratum of ice similar to those ordinarily found in the névé region. Regelation is complete and there arises what is known as a reconstructed, or regenerated glacier, with its strata leading to and dipping towards the region of accumulation. The weight of the ice here forces the lower strata to move out at right angles to the cliff face and a forward movement is imparted to the ice directly across the Mitre Glacier upon which it rests. This regenerated Lefroy moves about one-half as fast as the underlying Mitre, so that before the latter has reached the Victoria, the Lefroy has crossed to the opposite side of the valley. Between the hanging Lefroy Glacier and its bed there is being manufactured a certain amount of ground-morainic material, which is incorporated into the strata of the regenerated Lefroy, and moved across the valley as a result of its motion. While this is taking place, however, the Mitre is carrying the entire Lefroy down the valley and the actual motion of the débris is the resultant of these two motions by which there is accumulated at the base of Mt. Aberdeen a great heap of ground-morainic matter, with a dressing of angular material from the face of the latter mountain. The ground moraine rests upon the back of the Mitre and some of it is ridged parallel with its side, in which form it is dealt out to the Victoria and constitutes the main bulk of its right lateral moraine. This Lefroy Glacier is distinct from the Mitre, upon which it rests, in that it is a different type, is nourished differently, has a different form, a distinct set of strata unconformable with those of the Mitre, has a different direction of motion, a different rate of motion, and is accomplishing a wholly different geological work. The glacier is *parasitic* in the sense that it is carried by its host and is nourished from snow and ice that might otherwise be available for it. It is not parasitic in the sense that it draws its sustenance from the Mitre itself.

It is probable that glaciers of this type are now, and have been, more common than has been generally recognized. It seems likely that at a certain stage the glacier in a hanging valley would sustain more or less of this relation to the trunk glacier. By means of such a glacier we may account for the lateral transportation of materials across a valley and a transportation that would leave no record upon the bedrock. If two distinct glaciers may occupy the same valley simultaneously, it seems probable that two ice sheets of the continental type might be superposed, flowing in different directions, the upper delivering material to the lower.

5. Bear-den Moraines.

The bear-den type of moraine is so exceptional that some special explanation must be found by which we may account for the accumulation of coarse mountain

fragments without the usual filling of fine materials. The size of the blocks themselves is not so remarkable, knowing what a transporting agent a glacier is, as the *average* size of the fragments making up the moraines. In the case of four of the five glaciers studied, two of these moraines were found and only two. The absence of them in the case of the Yoho is readily understood when the lack of high cliffs is noted. Not one of the glaciers at the present time could form such a moraine, no matter how prolonged the halt. The blocks are angular and show no more glaciation than they might have received upon one face while they were in their original position in the cliff. The blocks were carried upon the ice and were not pushed or dragged along in front of, or beneath it. The fine material was not removed by the action of running water, as might have been done in other cases; but was absent from the first. If we are to account for these moraines we must load the glaciers with a mass ot exceptionally coarse blocks and only a minimum of fine débris. This cannot be done by assuming two periods of excessive weathering for they would produce as much fine material as coarse, and very probably a great deal more. The prevalence of the phenomenon prevents our resorting to the ordinary rock slide for our explanation. In the case of the Victoria it built a moraine of the ordinary type, then the two bear-den moraines, and then the present modern moraine essentially like the first. The Asulkan built its outer coarse moraine, then one of the ordinary type, then its younger coarse moraine and subsequently a series of the common variety. An examination of the various cliffs, in connection with each of the four glaciers, from which the material was most certainly derived shows that they all have a trend from north-northwest to west-northwest. A further suggestive fact is that in all cases the bulk of the material fell to the eastward.

During the season of 1904 no plausible explanation occurred to the writer, but upon leaving the field the idea of a double seismic disturbance came up and was carried back to the mountains in 1905. It seems now to be the only explanation by which to account for the phenomenon. Slipping may have occurred along some of the numerous fault planes traversing the eastern Rockies in a north-northwest direction and the region crossed by westerly moving seismic waves. From cliffs having a general northwest-southeast trend, blocks, already much weathered, would be detached and thrown eastward, comparatively few falling from the westerly facing cliffs. Glaciers most favorably situated for acquiring a load by this means, as the Wenkchemna, have the most massive deposits of the nature described; those unfavorably related to high cliffs, as the Yoho, appear to have made none. The great blocks detached by the earth jars fell into soft névé, or upon the yielding ice, and were not ground into small fragments as they usually are when they descend to the valley floors. The protection afforded the ice by the material brought about a halt of the front, until the blocks were deposited, when the general retreat was resumed.

It was reasoned that if the disturbances assumed reached from the Great Divide to the Selkirks, then many other glaciers, equally favorably situated for acquiring a load by this means, should show the same type of moraine, if they were not

tributary to other ice streams at the time. Further we should expect to find occasional rock slides of the same age as the moraines and cliff débris that did not reach the back of a glacier. The latter material not being concentrated would be inconspicuous. In 1905 there was but little time for a general examintion of the region but visits were made to the Horseshoe and Geikie glaciers. The former lies between the Wenkchemna and Victoria, with its main extent of vertical cliff extending to the northeast, but with a considerable portion extending from Hungabee to the Wastach Pass, with a westerly to northwesterly trend. Opposite this portion of the glacier there is a deposit of very coarse blocks, that were dropped upon the crest and outer slope of a still more ancient moraine, consisting largely of a stony till. The number, however, is very meager compared with those in the Valley of Ten Peaks, and would call for no exceptional explanation. A low ridge of coarse blocks occurs just inside, showing best about the front of the nearly detached western portion of the glacier, which is correlated with the inner of the bear-den moraines. In the case of the Geikie Glacier, lying at the head of Fish Creek Valley and nourished from the southern portion of the Illecillewaet névé (plate XXXIII), no moraines of the type sought were found within a distance of one and one-half miles of the nose. Although the cliffs are sufficiently steep to have supplied the material their general trend is northeast-southwest, *i. e.*, in the direction of supposed earth movement, and they suffered relatively little destruction. From the eastern face of Mt. Burgess there has been dropped a mass of coarse rock, which more strongly suggests the morainic deposit seen in the valleys than that seen anywhere else outside the reach of the glaciers. In many of the talus slopes there are many coarse and fine blocks, which look to be of nearly the same age, instead of showing the gradation that we might expect. In their work referred to upon page 4, Collie and Stutfield describe a mass of rock débris in the valley of the Athabasca (page 126) that may represent one of these ancient coarse moraines or a modern one in process of forming. In referring to peaks Woolley and Stutfield they say, "These two last mountains appeared to have been conducting themselves in a most erratic manner in bygone ages. A tremendous rock-fall had evidently taken place from their ugly bare limestone cliffs; and the whole valley, nearly half a mile wide, was covered to a depth of some hundreds of feet with boulders and débris. What had happened, apparently, was this. The immense amount of rock that had fallen on the glacier below Peak Stutfield had prevented the ice from melting. Consequently the glacier, filling up the valley to a depth of at least two hundred feet, had moved bodily down; and its snout, a couple of hundred feet high, covered with blocks of stone the size of small houses, was playing havoc with the pine-woods before it and on either side. In our united experiences, extending over the Alps, the Caucasus, the Himalaya, and other mountain ranges, we had never seen indications of a landslide on so colossal a scale." In a footnote they add, "The remains of a similar landslide were afterwards noticed blocking the outlet to Moraine Lake in Desolation Valley."

If the seismic theory furnishes the true explanation of these double massive moraines, then we have a means of correlating the positions of the extremities of all the glaciers showing them at these two stages in their history, also data for determining their actual retreat since and their relative rates. Glaciers, that were not tributary to others at the time, confined between steep cliffs, having a northwest to southeast trend, may be expected to show such moraines. There is the possibility that any particular glacier may have advanced since and have overridden one, or both, as the Victoria and Wenkchemna have partially done with the inner of their series. Numerous earthquakes must have occurred during the long Pleistocene period, but the cliffs were so completely blanketed in snow that we find no such records left in the trunk valleys. Similar moraines should be found in other sections of the world, but they might originate from the removal of the finer materials by running water, as well as by earthquakes and simultaneous rock slides. As to the actual age of these moraines we may only loosely speculate. The blocks *look* old and the schists and sandstones have disintegrated more or less, *in situ*, but undoubtedly they were badly weathered before the glaciers got possession of them. The age of the moraines is to be expressed in centuries rather than thousands of years. Based upon our vegetation data we may conclude that the inner of the two moraines was completed about five or six centuries ago and that the earthquake disturbance responsible for it may have occurred two centuries earlier. The outer of the two moraines seems to be about two centuries older.

6. Surface Features.

a. Dirt bands, zones, and stripes. In Chapter III of this report the writer has described and figured these three glacial features and has suggested that certain terms, used rather indiscriminately for any one, be restricted to a single feature. The first two are very often confused, one with the other, but are so essentially different in their real nature, if not always in their appearance, that they should be sharply separated and differently named. The *dirt zones*, or simply the *zones*, when the foreign matter is not present to discolor them, are the outcropping edges of the strata of which the glacier is composed. They show to best advantage about the nose and lower margins of the glacier that is sufficiently free from débris, as broad, parallel zones encircling the lower extremity and passing around to the sides where they disappear. They are usually convex down-stream, but the form they assume is determined by the configuration of the glacier's extremity. In case the stratification in the glacier is absent for any cause, there can be no zones seen.

The *dirt bands* are entirely superficial and result from the collection of fine débris in long hollows or troughs that first extend transversely across the glacier, but which become convex down-stream from the more rapid central motion of the ice. They occur in series, roughly parallel and regularly spaced, and assume finally a pointed, or hyperbolic form, which probably suggested to Schlagintweit the term "ogiven." The name "dirt band," however, was originally assigned

to them by Forbes, their discoverer, and is in more general use. The transverse, parallel troughs, in which the dirt bands have their origin, arise from the incomplete healing of transverse crevasses which occur at the crest of a steep ice slope. The lips of a crevasse, exposed to intense solar action are rounded more or less and when the crevasse closes there is left a trough which marks the position of the original crevasse. Into this depression wind-blown dust collects and is washed from the adjacent slopes. By absorbing heat this dust may emphasize the depression slightly and may render the ice somewhat spongy, as pointed out by Tyndall. If the ice slope is too steep, a cascade results and the ice is too much shattered to show the bands, or to allow them to form. If the slope is steep, but regular, with much melting over the surface, the site of the bands will be destroyed before any complete series can develop. Conditions are most favorable for their production upon the face of a moderately steep slope, which is immediately followed by a long stretch of gently inclined ice. They sustain no necessary relation, whatever, to the dirt zones, being present when the zones are absent. When both zones and bands are present they may be comformable for a greater or less distance and may be difficult to distinguish from one another. In the case of such a glacier as the parasitic Lefroy the zones and dirt bands may be discordant and intersect at high angles. There is reason for thinking that the dirt bands are produced annually, only the summer formed crevasses furnishing the necessary troughs, while the few winter crevasses completely and perfectly heal in passing down the slope. If this proves to be the case we have a means of determining the approximate yearly motion of the ice along the slope and a clue to the extent of the longitudinal compression, or extension, of the ice subsequently.

Where the edges of the blue bands, embedded in the more porous whiter ice, outcrop upon the surface, particularly along the margins of the glacier pressing firmly against the valley wall, there is developed a further miniature banding. The firmer blue ice melts less rapidly than the more vesicular layers and a series of parallel ridges and troughs results, the course, distance, and average breadth of which is determined by the ice structure itself. In the narrow troughs the fine dirt collects and the ice is marked with a series of delicate parallel dirt streaks. Tyndall compared them with the marks left in a gravel walk by a garden rake. Drygalski describes them under the name of *Schmutzbänder*, but this term must be reserved for the true dirt bands of Forbes. *Dirt stripes* suggests their appearance and will enable them to be distinguished from all the other dirt features. In that they owe their existence to the actual structure of the ice they have some relationship with the dirt zones, but in that the dirt of which they are composed is purely superficial, they are more nearly related to the dirt bands. They are to be seen at only a short distance, while the zones and bands are best brought out from a distant, elevated view.

b. Differential melting effects. Under favorable circumstances an interesting series of stages may be passed through by dust wells; dirt, sand, and gravel cones; boulder mounds; lakelets and morainic ridges. This was first worked out

by Russell upon the Malaspina for the lakelets and boulder mounds, but it applies also to the other features as well. Dust wells may persist through a season, or a series of seasons presumably, the dirt patches to which they owe their existence being continuously retained in the miniature wells. Although very shallow at any one time, their total depth might measure many feet. From wind action and small trickles of water more dust is being added slowly and in time there may be enough to protect the bottom, instead of causing its melting. The dirt now appears at the surface and the ice beneath melts less rapidly than the unprotected adjacent ice, giving rise to a miniature cone, marking the original site of the well. Such cones are found of various sizes and covered with dirt, sand, or gravel. By lateral melting the slopes eventually become so steep that the veneering slides off, or it may be washed down by heavy rains and distributed about the base of the ice cone. The bare ice is now attacked by the sun and a hollow is produced where the cone stood, about the rim of which stands more or less of the material by which it was covered. This material rolls and slides back into the depression as the sides are widened and steepened by melting. When enough has been concentrated at the bottom and about the sides to prevent further melting, the adjacent ice which has lost its protective cover, just in proportion as the depression has gained, now melts away to a level with the bottom and then still lower, causing the material collected in the basin to again assume the form of the cone. The miniature examples of this action might pass through these stages several times in the course of the season, while the boulder mounds and lakelets would require many seasons for the completion of a single cycle. In the case of a medial moraine, or a lateral resting upon ice of sufficient thickness, the same stages may be passed through, except that when the material is shed it assumes the form of a double ridge, between which the elongated trough is developed and into which the débris may slide to produce a single ridge again. In this way the superficial débris of a glacier may be subjected to much tossing and bruising before it comes to rest in the frontal or ground moraine. In the case of a débris-covered ice surface all that is necessary to start the process is to have the material unevenly distributed, a little thinner or a little thicker patch of foreign matter.

7. Ice Structure

a. Stratification. From a comparison of the thickness of the strata in the Asulkan with the available records of snowfall it seems probable that the strata in this glacier, as well as in the Illecillewaet and Yoho glaciers, represent the annual accumulation of snow in the region. The fall snows are combined with those of the following winter and spring, compacted by the summer's melting and rainfall into a white, porous stratum of granular ice. At any given place upon the névé by means of wind action a stratum may have gained, or lost in thickness. Owing to the deposition of the snow in successive layers and the periodic distribution of wind-blown rock débris, each stratum acquires a more or less distinct lamination; conformable with the stratum itself. During the

summer melting the fine dirt is concentrated at the surface, forming a soiled streak which contrasts strongly with the fresh snowfall of the fall. The water resulting from the surface melting and rainfall sinks into the stratum and contributes to the growth of the névé granules, forming a crust of different texture and color, by which the strata may be distinguished when no dust is present. In the case of a regenerated glacier, such as the Lefroy, the stratification results from periodic avalanching of snow and ice during the late spring, summer, and early fall. The strata may vary much in thickness and have no immediate connection with the amount of precipitation. They may become charged throughout with ground-morainic material and give rise to very distinct zoning. When a glacier is fed in part by névé snow, and in part by avalanches from hanging glaciers the stratification may appear very irregular, as in the case of the Victoria. In passing an ice cascade the stratification and lamination may be completely destroyed, or the uppermost strata may be destroyed and the lower more or less perfectly preserved, as pointed out by Reid. It is not supposable that the stratification could be thus destroyed and the more delicate lamination preserved. In the case of the regenerated Lefroy the stratification is restored, after having been lost, but it is not possible to restore the lamination completely, or regularly, in the case of such a glacier. It should be noted in this connection that under exceptional conditions shearing planes may be developed in the body of the glacier which do not coincide with the limiting planes of the depositional strata. In this way there may be acquired another type of secondary stratification having no relation whatever to that which originates in the névé.

b. Shearing. Observations upon the oblique front of the Victoria in 1904 indicated that the upper strata were moving bodily over those upon which they rested. The upper strata projected more and more daily, when there was not enough additional débris in the lower to account for the phenomenon by differential melting. A small amount of sand and fine gravel, washed down from above, collected in the lee of the upper projecting layers. Some days this was in small enough quantity to accelerate the melting of a narrow strip of ice upon which it rested, but quite as often melting was retarded by the material. At one place where the shearing action seemed pronounced three heavy spikes were driven into the base of the upper stratum and three corresponding ones in the face of the subjacent layer. These spikes were six inches in length and were driven horizontally into the ice until their heads were flush with the surface, about eighteen inches apart. The average surface slope of the ice was 46° and the vertical height of the ice 50 to 52 feet. The upper stratum had a thickness of about three feet, the lower two feet, and each contained, apparently, about the same amount of foreign matter, and this small in amount. At the beginning of the observations the upper stratum projected 19.7 inches beyond the lower (July 21), and by August 3, 25.6 inches, showing a gain in the 13 days of about six inches of the upper beyond the lower. The spikes were visited daily and reset and showed that while the upper stratum was advancing with reference to the lower it was also melting back more rapidly, because of its more exposed

position. The average daily melting about the spikes in the upper stratum was 0.23 of an inch in excess of that about those in the lower and proved that a differential movement of the strata was taking place.

c. Blue bands. It seems highly desirable to distinguish the minor stratification seams, originating in the névé, from the blue bands, blue veins, or ribbon structures, that have had an entirely different origin. The first step toward such distinction is to have a separate term for each of the two types of structure and the writer suggests that *laminæ* be used exclusively for the minor layers of which the strata are composed and that *blue bands*,[1] already in such general use, be restricted to the structures commonly included under the term, however they may have been produced. When they are each made the object of comparative study it should be possible to distinguish them. We should naturally expect the laminæ to become less and less distinct toward the nose, and to appear continuous, while we find the blue bands there showing very typically and being discontinuous. The same stratum might show both structures, either conformable, or cutting one another at various angles. In the case of simple glaciers, Agassiz and Reid have succeeded in tracing the laminæ from the névé to the nose. The structures seen in the Canadian glaciers are blue bands, rather than laminæ, since they are developed in great perfection where the strata have been completely destroyed, as in the case of the regenerated Lefroy and almost obliterated as in the Yoho and Illecillewaet glaciers. In general their position is at right angles to what may be assumed to be, or to have been, the direction of maximum pressure. They are seen best along the margins where the glacier is closely confined between rocky walls, extending parallel with the sides, dipping downward and inward at a steep angle. Beneath the medial moraine upon the Victoria they are vertical to fan-shaped. At the foot of ice cascades they may extend crosswise of the glacier. Having the same origin and being essentially alike, it does not seem wise to use different terms by which to separate these, such as marginal structure, longitudinal structure, and transverse structure, as suggested by Tyndall. Contorted patterns and faultings are to be accounted for by assuming differential movements in the ice after the formation of the bands.

When followed for a short distance, in either direction, blue bands are found to thin out to an edge and disappear, showing that they have a very flat, lenticular shape. Separate bands overlap and are felted together as are the bands in a schistose or gneissic rock. They strongly suggest schistosity in rocks and not stratification. The ice of which each band is composed is more compact, more free from air bubbles, and a deeper blue than the ice in which it is embedded. That they have been produced by pressure and stand at right angles to it, when in process of formation, as demonstrated by Tyndall, seems most probable. That

[1] The term *band* alone, or *banding*, as suggested by the glacial conference in August, 1899, is not fully satisfactory since it does not distinguish this structure from the dirt bands of Forbes. The following terms have been applied to this structure by various writers; Bandstruktur, Bänderung, Blaubänderung, Blätterstruktur, Blaublätterung, Blaublätterstruktur, blaue Bänder, blaue Streifen, Schieferung, Schichtung, parallele Struktur, stucture rubanée, structure lamellaire, ribboned structure, blue veins, blue leaves, blue bands, lamellæ, laminæ, lamination, and stratification.

these bands represent portions of the glacier that have been completely liquified by pressure, allowing the air bubbles to escape, seems, to the writer, very improbable, for four reasons. (1.) Blue bands occur in the basal layers, parallel with the valley floor. The thickness of the ice of an ordinary glacier is not sufficient to induce general melting by its simple weight. (2.) If the granular structure of the glacier is completely destroyed by melting, it cannot be reproduced by simple freezing, and still the granules are best developed in the blue band areas. (3.) Occasional granules may be found which extend from the blue bands into the adjacent vesicular ice. (4.) Water freezing in cavities in the body of a glacier should form a series of prisms, standing with their main axes at right angles to the ice surfaces bounding the cavity. Such filled cavities are found in the ice but they do not constitute blue bands.

d. Ice dykes. In connection with the Lefroy Glacier chiefly, there were noted in the early summer what appeared to be former crevasses, filled with ice and forming ice dykes in the body of the glacier. Some of these were cut by crevasses, testifying to their greater relative age and suggesting that they might persist from one season to another. A few of the dykes contained granular ice, the granules being moderately coarse, and were assumed to have been formed by the filling in of crevasses with ice avalanched from the hanging glacier upon Mt. Lefroy. Most of the dykes, however, were completely filled with a double tier of ice prisms, having their bases attached to the walls of the crevasse and extending horizontally out into the cavity, at approximately right angles. Generally the prisms met at the centre those from the opposite face of the crevasse and their inner ends interlocked. Sometimes a space was left between the opposite tiers of prisms. Ellipsoidal shaped spaces were also found completely filled with radially arranged prisms meeting at the centre. The explanation given for these features is that they were formed by the freezing of water in crevasses, and other cavities, in the spring, or early summer, while the glacier still retained a sufficient degree of its winter's temperature. The water was supplied by the early melting, or rains, and the freezing surfaces were the walls of the crevasse, instead of the lower stratum of the atmosphere, as is usually the case. Since in freezing, water forms a series of parallel prisms, with their axes lying, as a rule, at right angles to the surface of refrigeration, these prisms have the abnormal horizontal position, instead of the usual vertical one. Although the upper part of the dyke may have been lost by melting, there was no evidence that a horizontal stratum of ice had formed across the top from freezing induced directly by the atmosphere.

Drygalski has argued that it is *pressure* that determines the direction that the crystalline plates will assume when water is freezing, and that the main prismatic axes will lie parallel with this pressure. In the case of the ice of a lakelet or basin, after it has once been enclosed by the ice cover, the under side will be subjected to an upward pressure owing to the gradual expansion of the water as it is brought to the temperature of freezing. But the orientation of the basal plates, parallel with the upper

surface, began before the cover was completely formed and hence before such pressure could have come into operation. As pointed out by Mügge they also assume this position when an opening through the ice cover is artificially maintained. Mügge believes that the plates are simply floating in their position of equilibrium and that the pressure has nothing to do with the orientation of the plates. That this, however, is not the cause of the orientation is shown by the position of the columns in the ice dykes above described, where the plates have formed in a *vertical* position, while in the case of the ellipsoidal water-filled cavities they have formed at all angles between the vertical and the horizontal. In the case of the ice dykes the formation of an ice cover would have given rise to a lateral pressure, as well as an upward one, and the position of the plates in the horizontal columns would have been in harmony with the view of Drygalski. No trace of this cover, however, was seen, and it seems probable that the columns would still have formed at right angles to the cold walls of the crevasse, under none other than hydrostatic pressure.

Some experiments still in progress in the freezing of water in variously shaped vessels lead the author to believe that the basal plates are placed parallel to the surface of refrigeration, independently of pressure or position of equilibrium. The actual congealing temperature enters quiet water at right angles to this freezing surface, regardless of its position, and each successive plane of molecules in turn feels the effect of the crystallizing force. The result is that sheets of molecules are successively frozen parallel with the requisite isothermal surface as it slowly works its way into the body of the water. The orientation of the plates is facilitated by the fact that in making the ice crystal the molecules arrange themselves more readily (because of the superior crystallizing force) in the plane of the secondary axes than in the direction of the principal axis. This is shown by the form of the snowflake which has been produced supposedly under conditions in which the crystal was free to grow in any direction, so far as the supply of moisture and suitable temperature are concerned. As is well known the molecules are arranged mainly about the short main axis in the plane of the secondary axes. The principle is illustrated further by the frost crystals which form upon the window-pane, with cold air upon one side and a relatively warm, moist atmosphere upon the other. At first only a very thin layer of moisture, parallel with the surface of the glass, can congeal, and in this layer the molecules at once arrange themselves in the plane of the secondary axes. As the atmosphere supplying the moisture becomes cooled for some distance back from the glass the crystals may grow more or less irregularly. That the cohesive force in the ice crystal is much more powerful in the direction of the basal planes than in the direction of the principal axis, is demonstrated in the experiments to be noted later (p. 130). Pressures in a direction at right angles to the main axis will cause the basal plates to slide over one another, as in a bunch of tickets, but no such shearing action can be secured when the direction of pressure is parallel with this axis. According to the view of the writer the temperature con-

dition for the crystallization of the water is supplied successively parallel to the refrigerating surface, whatever may be its position or form, and the molecules yield to the relatively more powerful forces which are operative in the planes of the secondary axes.

e. Glacial granules. Glacial ice, which has not been subjected to a melting temperature, is firm, solid, and, apparently, homogeneous, except for air bubbles and foreign matter that it may contain. It is brittle, breaks without cleavage, and in quantity, when pure, has a rich blue color by transmitted light. Subjected slowly to a melting temperature there is developed a system of delicate capillary tubes, which form a network throughout all the ice affected, and extend into the body of the glacier a number of feet. These tubes outline the granules, more or less perfectly, of which the entire glacier is composed. These granules are irregular polyhedrons, of variable size, with curved faces which interlock with one another. Ordinarily there are no spaces between them that can be recognized and there is no cementing material to bind the granules together. They are observed to increase in size from the névé to the nose in any particular glacier and there can be no doubt but that the granules formerly in the névé are directly related to those seen in the lower part of the glacier. In the Canadian glaciers studied the largest granules were seen in the basal layers about the nose; the Asulkan, the smallest of the glaciers, having the smallest average granules, and the Yoho, the largest glacier, having the largest average granules. When subjected to considerable melting the capillary tubes become irregular and very thin spaces open between the faces of adjoining granules, allowing the granules eventually to fall apart, or to be easily pulled apart.

Each granule is an incomplete ice crystal, incomplete because its development has been interfered with by the neighboring crystals. Belonging to the hexagonal system of minerals, it has a single main axis, which is also its principal optic axis. In common with all known ice crystals it appears to be made up of a bundle of very thin plates, placed with their flat faces together, the axis standing at right angles to these plates. When the granules have melted apart the very delicate edges of these plates, or more probably sets of these plates, may often be recognized extending as delicate parallel lines about the granule and thus indicating the positions of the planes of the secondary axes. These lines are known as "Forel's stripes." They are referred to by Mügge as the "Translations Streifung," and were regarded by him as due to the partial shearing of the basal planes over one another. They are found, however, in newly forming crystals of ordinary lake or pond ice which have not been subjected to any shearing stress. Within the body of the granule there are seen, at times, circular disks of excessive thinness, with their flat faces perfectly parallel and all at right angles to the optic axis. They are of silvery whiteness and appear like "flattened air bubbles," as they were originally described by Agassiz (plate VI of Atlas, figure 10). These are "Tyndall's melting figures" and are cavities, "*vacuous space*," containing nothing more than water vapor, resulting from the internal contraction of the water, as it changes from its solid to its denser liquid condition.

The melting begins at certain points between the crystalline plates and spreads in a direction parallel to them, instead of across, or through them. The planes of these melting figures are parallel to Forel's stripes, and either feature when seen may be used for orienting the crystal. In addition to the stripes of Forel, there is to be seen a very conspicuous system of parallel ridges and furrows, covering the outside of softened granules, which can have no connection whatever with the crystalline structure. The ridges are either continuous, or consist of a series of regularly placed points, forming a wavy, irregular pattern about the crystal. The appearance suggests that seen upon the inside of one's finger-tips and thumb. It shows itself when the adjacent faces of the granules begin to separate and is due to differential melting at the surface, but it is far from clear what could give rise to such a regularly irregular pattern.

By means of the polariscope it was found that there is a tendency towards the orientation of the granules about the nose of the Victoria, Yoho, and Illecillewaet glaciers, the other two not being tested. The Victoria shows distinct stratification about the oblique front, the Yoho indistinct, and in the case of the Illecillewaet, the stratification about the nose seems to have been completely destroyed. Vertical sections of the ice were prepared, cut crosswise and lengthwise, and these were compared with horizontal sections and oblique sections. It was found that there is a marked tendency to arrange the optic axes of the granules in the basal layers near the nose in a vertical position, from one-fourth to one-third of them being estimated to be so oriented. The cause of this orientation is not yet apparent, but connected, undoubtedly, with the method of growth of the granules themselves. In order to account for the orientation which he found in the Greenland glaciers, Drygalski assumed that the granules were separately melted and refrozen with their axes parallel with the direction of pressure, which he considers at right angles to the strata. If it is true that the direction of pressure determines the position that the crystalline plates will assume, and hence the position of the optic axes, which the writer seriously questions, then the space occupied by a single crystal, which has been completely melted, should contain a large number of radially arranged prisms, each standing at approximately right angles to the portion of the ice surface to which its base is attached. Owing to the law of transmission of forces by a liquid the pressure is equal in all directions whether this pressure arises from the weight of the superincumbent ice, or because of the expansion of the water in the closed cavity just before freezing. Drygalski is in error in supposing that the pressure experienced by the liquified granule is *vertical* only, since, if confined, the water would press outward in *all* directions. In case the position of the refrigerating surface, or surfaces, is the cause of the orientation of the plates, then in the closed cavity occupied by the liquid granule, there should be formed a mass of radially arranged prisms, similar to those observed by the writer upon the Lefroy and by Agassiz upon the Aar. In either case, the cavity should be filled with small radially arranged prisms and not by a single crystal with its axis in a vertical position. This furnishes rather conclusive evidence that granules and blue bands never have existed in a com-

pletely liquified condition. That they may have been melted partly upon one face and frozen upon another, or the water derived from one by melting added to another granule, is in harmony with known properties of ice. Pulfrich found that when an ice crystal was pressed against a wet surface of glass and allowed to freeze the water between the ice and plate was incorporated into the crystal, so as to make a homogeneous mass.

Much interest is attached to the methods of granular development, since the more modern theories of glacial movement are more or less dependent thereon. It has been shown by Emden, Drygalski, Crammer and others that when névé granules are made into a water slush, such as might originate from excessive melting, or heavy rainfall, the granules grow in size and, under favorable conditions, quite rapidly. In the névé as well as in the body of the glacier, however, there must be a maximum limit which the granules may attain by this means for the ice will presently become too compact for more water to enter and no space will be left for the growth of individual crystals.[1] That further growth of the granules does not take place by the simple freezing together of neighboring granules, is conclusively shown by the homogeneous structure of the mature granule. That new granules cannot originate by the complete and simultaneous melting of a number of adjacent smaller ones, is believed to have been just shown in the preceding paragraph. Of the various theories of granular growth remaining we may recognize three divisions, based upon evaporation, melting, and "dry union."

First.—It has been shown by Chamberlin and Salisbury that in dry granular snow, kept continually below the freezing temperature, certain granules will grow in size at the expense of the others, presumably by the giving off and congealing of water vapor.[2] In the porous snow of the névé it seems probable that the principle would be operative and that the granules would diminish in numbers and increase in size, even when not immersed in water. For the body of the glacier, with the granules in such intimate contact, the authors do not believe that evaporation and condensation can take place to any appreciable extent.

Second.—Making use of the principle of Thompson that ice may be melted by pressure, without any change in temperature, many investigators, as Mügge, Drygalski, Chamberlin, Crammer, etc., have accounted for the growth of the granules in the main body of the glacier by assuming a partial or complete melting and refreezing. Those granules which owing to their location are subjected to the greatest pressure, or internal friction, or those portions of granules similarly affected will melt, thus redistributing the pressure and allowing the free molecules to attach themselves to the most favorably located granules. The liquefaction of the granules may be confined to their outer surfaces, or, as Drygalski believes, take place locally in the bodies of the granules. Chamberlin believes that the granules

[1] See Hagenbach-Bischoff's criticism of Forel's infiltration theory, "Weiteres über Gletschereis," *Verhandlungen der Naturforschenden Gesellschaft in Basel*, VIII, 1889, p. 822.

[2] *Geology*, vol. I, Chamberlin and Salisbury, p. 296 (Chamberlin, Peet, and Perisho). "A Contribution to the Theory of Glacial Motion," Chamberlin, Decennial Publications of the Univ. of Chicago, vol. IX, p. 194.

are subjected to more or less of a rotary movement and a sliding along their limiting surfaces, by which the internal stresses of the glacier are undergoing constant readjustment and the ice mass permitted to move under the influence of gravity. These views of granular growth would call for constant changes in the form, size, and number of the granules and in their relative position.

If the principles underlying these views—melting under pressure or friction—were alone operative in granular growth there should occur a much larger number of smaller granules mingled with the larger in the basal layers about the nose of a glacier. Owing to the manner in which the granules are keyed together the strain upon the smaller would be relieved as they diminished in size and would be transferred to the faces of the larger neighbors. Lying in between the coarser granules we should expect a considerable number of these smaller remnants, but such occur only somewhat sparingly. The remarkably well preserved blue bands in the basal layers about the nose of the glacier furnish conclusive evidence it seems to the writer that the granules have not been destroyed since the bands were produced and that they have not materially shifted their position with reference to their neighbors. Upon the surface of the lower Asulkan Glacier these bands were found so thin that thirty were included within the distance of four inches, several necessarily cutting across adjacent granules. Any perceptible shifting of the granules as the result of sliding or rotation would give rise to faulting of these bands, while their destruction by either slow or rapid melting would cause abrupt gaps in the continuity of these bands. The preservation of the depositional laminæ from the névé to the nose would seem impossible if the granules are being destroyed and reformed or rotated out of their original position with respect to their neighbors.

Third.—The "dry union" of granules described on page 40 of this report accounts for the reduction in the number and an increase in their size toward the nose of the glacier. According to this theory the molecules of the yielding granule give up their own crystalline arrangement and without any apparent melting are immediately incorporated into the body of the controlling granule. Heim's view was that such a union could occur only when the main axes of the two granules were placed in approximately parallel positions,[1] but the experiments of Hagenbach-Bischoff showed that such union could occur regardless of the position of the axes,[2] and this he regarded as the true cause of granular growth in the glacier. This view was accepted by Emden in his prize essay, "Ueber das Gletscherkorn," published in 1890. It furnishes the simplest theory of granular growth, not of glacial motion; accounts for whatever uniformity exists in the size of the granules, calls for no shifting of the granule relative to its neighbors, and hence permits the continuity of laminæ and blue bands.

[1] *Handbuch der Gletscherkunde*, 1885, s. 330.

[2] *Verhandlungen der Naturforschenden Gesellschaft in Basel.* Bd. vii, 1888, s. 192; Bd. viii., 1889, s. 635 und 821. *Archives des Sciences physiques et naturelles*, T. xxiii., 1890, p. 373.

8. Theories of Glacial Motion.

The one question that continually arises in the minds of all glacial students, with tantalizing frequency is—what is the nature of this glacial motion? Are we any nearer an acceptable hypothesis than we were nearly seventy years ago when the serious study of glaciers was begun? Possibly! Without attempting the discussion here of the various theories that have been proposed, the writer desires to record his convictions after his Pleistocene studies in the Lake Erie region and his four consecutive seasons about the Canadian glaciers. All are now agreed that sliding, expansion by freezing or changes in temperature, general melting under pressure and regelation cannot fully and completely account for the known facts of glacial motion. Probably all will admit that, under certain circumstances, every one of these factors may find its application. In the névé region it is possible that a certain amount of rolling and sliding may occur amongst the granules, producing some motion, such as we may see in a pile of beans or peas. Farther down in the glacier, although the granules are intimately interlocked, it is quite probable that they would permit of a certain amount, possibly considerable, motion between their adjacent faces. If we introduce the idea of a partial melting of the granules, those portions of them subjected to especial stress, or friction, will yield under the action of gravity working from above, or behind, and will permit other granules to yield. Upon relief of pressure, the water will be frozen to the original granule or distributed to neighboring granules, as discussed in the preceding paragraph, and thus the movement of the glacier may arise entirely from the alteration and growth of its component granules. We must assume that the heat necessary for the partial liquefaction of the granules is developed within the glacier as the result of pressure and friction and not that it is derived from the atmosphere, or the bed.[1] However, any heat communicated from such a source will make it that much easier for internal changes to take place. As presented by Chamberlin and Salisbury, this theory of granular change accounts more satisfactorily for the glacial phenomena observed than any other, in which no molecular movement of the solid granules is assumed.

The original idea of plasticity ascribed to glaciers by Rendu and developed by Forbes is based upon the conception that the molecules of firm ice will yield continuously to a stress, without producing visible rupture. The stress may be of the nature of a thrust, or of tension. This theory has been rejected by the most prominent physicists who have turned their attention to the problem of glacial motion, because of their unwillingness to admit that ice could possess this and certain other properties apparently inconsistent with plasticity. The difficulty so far as rigidity alone is concerned is removed by our knowledge that such substances as lead, tin, and iron may be made to flow by pressure, under ordinary temperatures. As soon as direct experiments were made to test the plasticity of ice it

[1] In a recent pamphlet entitled, "The Viscous *vs.* the Granular Theory of Glacial Motion," Mr. O. W. Willcox has endeavored to show that the heat developed through pressure or impact of the granules would be conducted away as rapidly as it is generated (p. 18).

was found that bars of ice frozen in a mould, or cut from a glacier, may be bent, elongated, compressed, and twisted, without visible rupture, even when kept continuously below the freezing temperature. These experiments were made by Main, McConnel, Kock, and Mügge and show that solid ice, made up of a collection of irregular crystals, is decidedly plastic. McConnel calculated that the amount of extension required of the ice in the Rhone Glacier, because of the more rapid central movement when compared with its sides, amounted to 0.0029 millimeter per hour, for each 10 centimeters of length. In his experiments with bars of glacial ice, but one of the three bars tested showed as small amount as this and that for only a portion of the experiment. In the case of single crystals they were found capable of continuous yielding without rupture, providing the pressure was applied at right angles to the optic axis, the movement appearing to consist of a sliding between adjacent crystalline plates. When the force of compression, or tension, was applied parallel with the axis, the result was exceedingly small, or *nil*.[1] The verification of these results by other investigators leads to the conclusion that ice is capable of showing a certain type of plasticity, although different from that ascribed to it by Rendu and Forbes. An amorphous plastic substance yields under a suitable stress in any direction without visible rupture. A crystalline substance which maintains its definite molecular arrangement will be limited in the number of directions in which it may yield. If ice crystallized in cubes it seems likely that it might have yielded without rupture in three directions. Had it crystallized in square prisms we may now conceive of a movement in two directions. In the hexagonal system in which it actually crystallizes the molecular cohesion measured in the direction of the main axis is of a sufficiently different nature from that at right angles to it to permit of a gliding of the basal plates without rupture and the destruction of their molecular arrangement. *This is plasticity in a crystalline substance.* The experimental results were obtained with moderate stresses and much below the freezing temperature. In the case of a glacier under great stress and a temperature near the freezing point it seems absolutely necessary that the glacial granules should manifest this property to a greater or less extent, regardless of the actual mechanics of glacial movement.

A number of phenomena, noted upon the Canadian glaciers, has convinced the writer that a certain amount and kind of plasticity is a fundamental property of glacial ice. The complicated patterns occasionally shown by the blue bands are such as might arise from plasticity, but not from melting or rotating of the granules. When similar effects are seen in ordinary rocks they are commonly referred back to a plastic condition of the matrix. It was noted that when the difference in the rate of movement between the centre and margins of the glacier is sufficiently small, there are no marginal crevasses to be seen. This implies that the ice permits a certain amount of stretching, without visible rupture. If ice were absolutely incapable of yielding under tension, any appreciable difference be-

[1] "On the Plasticity of Glacier and other Ice," James C. McConnel, *Proc. Roy. Soc. of London*, vol. 44, 1888, p. 331; "On the Plasticity of an Ice Crystal," vol. 49, 1891, p. 323.

tween the rate of movement of center and sides must open marginal crevasses. In the rock scorings seen near the nose of the Illecillewaet, the frontal and lateral grooves about the knobs and trails suggest very strongly a plastic condition of the ice. In the case of the same glacier, but farther up between the ice and the left lateral moraine, the ice was seen moving over a knob of bedrock not fully exposed in 1904. Transverse crevasses formed above while the ice melted below and there were formed strips of ice, 20 to 25 feet long, supported at either end. Moving downward these strips were suspended in the air, and in the course of ten days in September one bar had sagged so as to be very noticeable to the eye, without forming any crevasse large enough to be noticed, or to permit of the destruction of the ice bar itself. This phenomenon seemed to indicate that the ice could, to some extent, yield to a tensional stress.

Now that the question of the plasticity of granular ice has been settled by experiment, what objections are there that may be urged against its application to the glaciers? Crevasses and faultings indicate simply that there is a limit to its plasticity, as indeed there is to the most typically plastic solid. The *tendency* to flow must be greater in the basal layers, but it does not necessarily follow that with the friction of the bed to combat, the velocity here will be greater than or even equal to that of the upper layers. The hold which glaciers have upon rocks in their basal layers is probably not a firm one. It seems to the writer that the chatter-marks, crescentic gouges, the shape and often sudden termination of the coarse striæ, as well as the faceted condition of the boulders in the ground moraine, all indicate that the glacier was persistent, rather than firm, and that it very often lost its grip. All of the phenomena of rock scoring, the subglacial fluting of the ice, the compression of the ice at the base of a slope, the phenomenon of shearing, and the mounting of reversed slopes prove that portions of the ice move bodily under the influence of a more or less rigid thrust from behind. This necessary amount of rigidity in the ice is not inconsistent with the degree of plasticity ascribed to it. When the flow is not sufficiently rapid at any point the ice must be thrust forward bodily. The most forcible argument against this modification of the viscous theory of glacial movement is brought forward by Chamberlin. It would seem that the granules should be distorted noticeably in the direction of flow. That this distortion is not more apparent may be due to the complete mechanism of granular growth. It may be disguised by the shearing of the granules in the direction of the basal planes and their later dry union by the principle of Hagenbach-Bischoff.

9. Color of Ice and Glacial Water.

The exquisite richness and variety of coloring seen in glaciers and glacial lakes constantly arouses the wonder and admiration of those privileged to gaze upon them. The colored photograph fails to reproduce it and it eludes the brush of even the most skilful artist. An explanation of the cause of this coloration can scarcely fail to be of interest. In 1904 a study was made of several

of the lakes by means of standard solutions of copper and nickel sulphate and an instrument devised from a stereoscope. By using measured amounts of the solutions and mixing with pure water it was possible to match the water and to express its color as an equation, from which the depth and shade of color might be at any time reproduced. The solutions were prepared by dissolving 30 grams of the chemically pure salt in 100 cubic centimeters of distilled water and were placed in a thin glass "cell," with parallel sides, the inside measure of which was 8 millimeters. A reflector was so arranged that the water could be viewed directly, while the fluid mixture was seen by reflected diffused light. The proper proportions could then be obtained by experiment. The shade of color changed somewhat by the condition of the sky, the position of the observer, the time of day, and the strength of the wind. In the case of Moraine Lake the depth of blue was too intense in the quiet of the early morning to be matched by the pure copper sulphate solution, in a cell of the above thickness. A slight breeze sprang up and lightened the shade sufficiently. The table below gives the color simply at the time of observation and under the conditions then prevailing.

COLOR OBSERVATIONS UPON ROCKY MOUNTAIN LAKES.

Lake.	Date.	Time.	Proportions in cubic centimeters.	Sky.
Lake Louise	Aug. 3.	8:45 A.M.	29 c.c. green + 10 c.c. blue + 65 c.c. water.	Clear but hazy.
Emerald Lake	Aug. 16.	8:00 A.M.	10 c.c. green + 10 c.c. blue + 50 c.c. water.	Fair.
Moraine Lake	Aug. 10.	10:00 A.M.	3 c.c. green + 30 c.c. blue + 23 c.c. water.	Sunny.

As the season advances a marked change occurs in the color of the water of Lake Louise, there being much more blue in the lake in the early part of the summer and more green towards the fall. Mr. Robert Campbell informed me that a decided change has occurred in the color of the water of Emerald Lake in the last few years, it being more of an emerald when he first saw it and now he considers it more of a turquoise. In discussing this change with Mr. Bell-Smith, the Canadian artist, I learned that he had observed the same change since 1888, there being a very noticeable increase in the amount of blue.

Some simple observations and experiments in the field made clear to the writer the cause of the differences in color of the water of different lakes and the changes that occur in the same lake. It had been remarked before, but it was left for Bunsen to demonstrate that absolutely pure water is blue, as seen by transmitted light.[1] The colors with the longer wave-lengths, as yellow, orange,

[1] "Ueber den innern Zusammenhang der pseudovulkanischen Erscheinungen Islands," *Annalen der Chemie und Pharmacie*, Bd. LXII, 1847, p. 1. Previous to the time of Bunsen the illustrious scientists, Newton Humboldt, Davy, Arago, and Forbes had speculated upon the problem but with only meager results. Later Beetz, Tyndall, Bezold, Boas, and Aitkin had more or less completely grasped the idea of *selective absorption* and gave us a satisfactory theory of the various modifications of the color of water in nature.

"Ueber die Farbe des Wassers," von W. Beetz, *Annalen der Physik und Chemie*, Bd. CXV, 1862, s. 137 zu 147.

The Glaciers of the Alps, chapter 6, Pt. II, Color of Water and Ice, 1860, Tyndall.

Lectures on Light, Tyndall, 1877, p. 35.

Theory of Color, Wilhelm Von Bezold. Translated by Koehler, 1876, pp. 41 and 67.

"On the Color of the Mediterranean and Other Waters," Aitkin, *Proc. Roy. Soc. of Edinburgh*, XI, 1882 pp. 473 to 483.

and red, are absorbed if passed through water of sufficient thickness. While of the colors at the other end of the spectrum, with the short wave-lengths, blue is the one which water is chiefly able to transmit, violet and green being also transmitted, but less perfectly. Bodies of pure water of a volume sufficient to absorb the longer waves of light reflected from the bottom, but not so deep as to absorb it all, will appear blue. This blue is not reflected from the sky, although the condition of the sky will affect the tint. Lakelets in the névé, such as the one discovered upon Sapphire Col by Mr. Wheeler, are a rich blue; those upon the ice may be blue, or not, depending upon their freedom from sediment, being liable to change rapidly. Moraine Lake (plate xxv) owes its exquisite blue color to its purity and depth. Water in the form of ice possesses still the same power to transmit the colors with the shorter wave-lengths, violet, indigo, blue and green, with the preference for blue. If a mixture of these four colors, or of all the others which compound white light, be passed through a block of pure ice, of sufficient thickness, none but the blue will emerge. If no light whatever is being transmitted through either ice, or water, it will look black, or will show whatever color of light is being reflected from its surface.

From this blue as the fundamental and natural color of ice and water by transmitted light we meet with many modifications in nature. Finely divided ice, as snow and névé, presents innumerable reflecting surfaces from which light of any and all colors is sent to the eye. The same is true of water lashed into foam, or in any finely divided state, as fog, cloud or condensed steam. In ordinary light these forms of water and ice appear white, but in the gorgeous colors of the sunrise and sunsets they transmit to the eye by reflection the greatest variety of color. Névé begins to show a bluish tinge as soon as the transmitted light begins to predominate over that which is being reflected. The water which issues from the glacier is generally charged with sediment, and if this is much in amount, its color will determine the color of the water of the drainage brook. It generally appears a milky, or creamy, white but may be a dirty gray. With the deposition of the coarser yellowish sediment and the retention of the very finest, if the volume of water is considerable, the water assumes a greenish tinge, as seen in the Asulkan and Illecillewaet streams. With the loss of this sediment the stream acquires more and more of its natural blue. When this glacial sediment is introduced into a lake in sufficient, but not too great, quantity the water becomes charged with finely divided rock particles in suspension. These particles are able to reflect the longer waves of the spectrum, particularly yellow, but also the closely related green and orange, while they very effectually cut out the shorter wave-lengths giving rise to violet, indigo, and blue. The result is that there are introduced into the water innumerable reflecting faces which are capable of sending to the eye only those colors that lie at the centre of the spectrum and towards the red end. But the only light that is available for reflection is that which has already passed through the water once and had its yellow, orange, and red to a greater or less extent filtered out. That which remains to be reflected by the foreign particles will pass again through the water and will suffer

still further absorption. Of the blue and green rays, which make their way readily through the water, only the green rays are reflected by the particles and these alone reach the eye. The quantity of light is thus much reduced in amount, but with the sun shining upon the lake the green becomes quite vivid if the water carries the requisite amount and kind of foreign particles. If the foreign particles were pure white they would be capable of reflecting all colors equally well, and the rich blue of the water would be brought out in perfection.

In the case of Lake Louise, we have a variable amount of sediment entering the lake during the year, and consequently a seasonal variation in the color of its water. With the very slack drainage during the winter, the sediment, in considerable part, settles and the water in the spring shows more of its own blue color. With the increased activity and melting of the Victoria Glacier the supply of sediment delivered to the glacier increases as the summer advances and the water becomes a richer and richer green. About the delta at the head of the lake the sediment is so abundant and lies so near the surface that the water is unable to absorb the yellow, and the color of the sediment itself is seen with little or no modification. In the case of the change in color noted for Emerald Lake we may infer that the drainage stream at its head has been carrying less sediment than formerly. It is not improbable that the diminished activity of the inlet may be connected with the stage of diminished precipitation recently closed and that the rich emerald green of the lake in 1888 and earlier was connected with the stage of increased precipitation, which is supposed to have closed in the early 80's. With an increase now in the average annual precipitation it will be interesting to see whether the lake returns to its former shade of color.

The introduction of green or yellow, organic solid matter, animal or vegetable, into the body of water would have the same effect. If the lake is sufficiently shallow and the bottom covered with green vegetation, or yellow sediment, the water will not be able in the short transmission to cut out the green and this color may appear in lakes of water free from sediment. About the margin of Moraine Lake the water has a greenish cast for this reason. Organic matters in solution quite generally give water a yellowish to brownish color, as seen naturally in bogs and artificially in tea, coffee, cider, beer, etc. With the above principles in mind one may infer from a glimpse of a distant lake the condition of the water and the state of activity of glaciers whose drainage streams empty into it. If upon rounding the shoulder of Mt. Temple, in entering the Valley of Ten Peaks, the first glimpse of Moraine Lake showed that a rich green had been substituted for its superb blue, one might safely infer that the Wenkchemna Glacier had begun to erode its bed although a neighboring rock slide might temporarily give such a result. Even the names of lakes in a glacial region are suggestive of the amount of glacial activity in the valley, such as Sapphire Lake, Turquoise Lake, and Emerald Lake.

The same principles of coloring apply to ice as well as to water. When highly charged with sediment of any particular color, its own natural color is obscured and the color of the sediment is sent to the eye with little or no modification.

If, however, yellowish sediment is distributed through the ice in proper proportions the case is identical with that discussed for water, and the ice assumes a greenish cast. In the case of the solid ice the sediment can not be assorted and evenly distributed as in the case of water and hence only greenish patches and streaks occur, just where conditions are favorable. It has not seemed appropriate to any one to apply the names "emerald," or "turquoise," to a glacier while "sapphire" would not be very distinctive. By applying the principles here set forth we may account for the coloration of glaciers, the lakes in their neighborhood; the gorgeous pools of blue and green water in the Yellowstone Park and similar regions, the blue color of the ocean and the seas, the green and final yellow strip as we approach the shore and such phenomena as the blue and green grottoes of the island of Capri. No one has yet satisfactorily explained how a considerable body of pure water may appear limpid.

THE END.